HEIGHT ADJUSTABLE WHEELCHAIR SEAT DESIGN

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By

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HEIGHT ADJUSTABLE WHEELCHAIR SEAT DESIGN

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I am writing this very first thesis in United States with my sincere appreciation to all those who have advised me, helped me, and guided me through completion of Master of Industrial Design program.

I am extremely honored to devote my time in Georgia Tech to designing tools that will assist disabled people with everyday life, since I have the similar feeling of in need of help when I first came to this country from a very different culture environment. Disabled people are in need of help both physically and psychologically. To investigate their needs from their unique perspective and create universal design product for this group of people require a heart with patience, consideration and caress. I was fortunate to have received it as I came here with “culture disability”. And through the two-year education in Georgia Tech, I grew up and finally got adapted to the environment here. I could never do that without help from all my classmates and instructors. Now I sincerely hope to express my grace to anyone who needs help by designing products for disabled people, those who need more help and assistance.

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SUMMARY

Full time wheelchair users are at a height disadvantage during many function activities, such as transferring or reaching. Retrieving objects from the ground or a higher shelf while seated in the wheelchair can be both difficult and unsafe. Lateral transfers between surfaces at different heights can be hard and unstable. Sit-to-stand transfers are made simpler with a higher seat. This research project seeks to assist reach and transfers by designing a system to raise and lower a wheelchair seat over a 4’’ range.

The project followed a multi-step iterative design process that included: 1) needs assessment by conducting interviews and surveys, identify design needs from different stakeholder groups; 2) analysis of stakeholder groups’ feedback and synthesis into design criteria; and 3) creation of design concepts for the adjustable height wheelchair seat; 4) evaluation of the design by setting up heuristic evaluation criteria and performance of user testing; 5) design revision based on user’s test performance and feedback. The design process included fabricating and testing of various concepts, validating design through user testing, and addresses technology transfer of the device.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Improper seat height can impact the safety and function of wheelchair users while performing daily tasks. (Kirby, 1994 & Nelson, 2003) Currently, only select power wheelchairs with elevating seats offer the function of height adjustment. This function has a high cost and adds complexity to the wheelchair. This project seeks to design and test a height adjustable device for manual wheelchairs.

Potential users of the proposed adjustable height wheelchair seat include wheelchair users who use foot propulsion, and users who have difficulty transferring and reaching items in their environments.

1.1.1 Reaching

Reach restriction can be easily understood based on the height of a user and seat height in a wheelchair. Tony Toppses (Toppses, 2002) said that it is difficult to reach objects higher than arm's reach due to the restricted wheelchair seat height. Even if one employs a device such as a reacher, the lack of fine dexterity and tactile feedback can become a problem when manipulating objects.

Full time manual wheelchair users who frequently reach upward or downward to retrieve or access objects can significantly benefit from adjustable seat height. Retrieving objects from the ground or a higher shelf while seated in the wheelchair can be both difficult and unsafe. Frequent overhead reaching activities can contribute to chronic overuse injuries and shoulder pain. (Sigholm G, 1984) Stretching to access items just out of reach may put people at risk of falling or tipping over.(Kirby, Ackroydstolarz, Brown, Kirkland, & Macleod, 1994) (Nelson et al., 2003) However, as shown in Figure **1**, slight changes in seated height may facilitate reach to increase function as well as safety and comfort.

a) Insufficient seat height for reach **b) Elevated seat height for easy reach** **c) Unsafe height for reaching down** **d) Lowered seat height for safe reach**

Figure 1: Upward and downward reaches at different seat heights

1.1.2 Transferring

Transferring in and out of a wheelchair is necessary at least once a day for almost all wheelchair users with the frequency and reasons for transferring varying greatly depending on the person. Various activity levels, perception about the hassles of transferring, and the strength required to successfully transfer may determine how frequently a person transfers. Transfers can be generally grouped as lateral or sit-to-stand transfers. Lateral transfers are used by people who cannot stand so transfer laterally from one surface to another. This may be accomplished with or without a transfer board and can be done independently or with assistance. Sit-to-stand transfers involve rising from the seat and pivoting or stepping to another surface before sitting. These transfers can be done independently or with assistance.

1.1.2.1 Lateral Transfers

Lateral transfers can be made easier and safer with slight changes in seat height. (RESNA, 2005) Transfer accidents are more likely to occur when the two involved surfaces are not level. Kirby found that transferring accounted for almost half of the injuries sustained by the manual wheelchair users, and negotiating uneven surfaces further increased the incidence of injury for those performing lateral transfers (Kirby, et al., 1994). Nelson said that transfers have also been identified as the activity most frequently associated with fall-related fractures in wheelchair users (Nelson, et al., 2003). Transfers across two surfaces that are not level impose increased demands on the arm muscles (Koontz A, 2009). Bjelle reported that level seated transfers require less shoulder power and therefore, induce less shoulder pain and stress (Bjelle, Hagberg, & Michaelsson, 1979). This research was corroborated during an interview discussing the seat height adjustment device, with one interviewee stating: "down is easier than transferring up" (Paris, interview, 2/23/2010). However, transferring downward can also be problematic as one must maintain body control when decelerating downward. Figure **2** illustrate the difference of transfer in different seat height wheelchair. Note the angle of the transfer board when transferring from a low seat to a seat raised by 2".

a) Transferring upward from standard height

b) Level transfer after seat elevation

Figure 2: Lateral transfer at different seat heights

1.1.2.2 Sit to Stand Transfers

Tinetti et al. found high occurrences of falls during sit-to-stand among older adults. (Tinetti, Speechley, & Ginter, 1988) Hughes and Schenkman said that many elderly people have difficulty with the common functional activity of rising from a chair, and a low seat height chair makes it even more difficult for elderly wheelchair user to complete the sit-to-stand task.

"functionally impaired elderly, when rising from their lowest successful chair compared to a chair of knee height, significantly increase peak hip flexion velocity (11 degrees/sec, $p < 0.01$) and time to rise (1.25 sec, $p < 0.01$), and significantly decreased their mean center of mass/base of support (COM/BOS) separation at lift-off (1.96 cm, $p < 0.05$)."(Hughes & Schenkman, 1996)

Sit-to-stand transfers become easier and safer from a higher seat. Unfortunately, for those who propel with their feet, a lower seat height is necessary to reach the ground resulted in a more difficult transfer (Figure **3**).

a) Difficult sit-to-stand transfer from 'hemi' height seat **b) Elevated seat height for easier sit to stand**

Figure 3: Sit to stand transfer at different seat heights

1.1.3 Environmental Access

When using tables or desks, wheelchair users may benefit from adjusting seat height. Due to the different design of furniture, different styles of tables often have different heights. For example, when wheelchair users are dining out in restaurant, it is very important for them to have enough knee clearance under the table surface. Alternatively, the table height might be too high for them to use the table comfortably. In both situations, an adjustment in seat height can facilitate better environmental access.

Height adjustability in wheelchair seat can also help wheelchair users adapt better in public places. For example, when watching movies at cinema or watching drama at theatre, the accessible seating is usually positioned in the front or back row. A height adjustable seat height may allow the wheelchair user to better enjoy the show by adjusting seat height to an optimal position.

1.1.4 Foot Propulsion

Rappl and Jones say that if the client is able to foot-propel, the height of the seat upholstery and the seat cushion combined must be low enough to adequately reach the ground (Rappl & Jones, 2000). Schmeler & Buning say that a “wheelchair can come lower to the floor for easier propulsion by foot” (Schmeler & Buning, 1999). For foot propellers, appropriate height of the wheelchair seat from the floor can facilitate optimal wheelchair propulsion (Behrman, 1990).

In the current market, manual wheelchairs usually have seat heights of 17 ½’’and 19 ½’’. The higher height is standard whereas the 17 ½’’ seat height is used by persons who propel using one or both feet. A few wheelchairs can be configured to both heights by changing axle position but it is impossible for user to change wheelchair height manually while they are still using it. Powered seat elevators are an option for power chairs but not manual wheelchairs.

The proposed Height Adjustable Wheelchair Seat Design is a unique product in that it will target manual wheelchair users, offering both lowering and raising, to assist with reaching and lateral and sit-to-stand transfers and be useful for both upper extremity (UE) and foot propellers. Not all manual wheelchair users will need or desire such a device since it will certainly add weight to the wheelchair and moving parts will add complexity that will be undesirable for some users. However, this technology may serve an important need for some users.

1.2 Objective

The objective of this project was to design, fabricate and evaluate a height adjustable seat for manual wheelchairs. The proposed design will meet the criteria resulting from interview and survey with stakeholder groups. A prototype will be fabricated that meets most of the desired functional and operational requirements. Evaluation of the prototype will provide evidence and reference to further optimize the design and proceed to an iterative design result.

1.3 Specific Aims

a) Establish needs based upon current products and stakeholder input

Design needs were identified by conducting interviews and surveys with two primary stakeholder groups: individuals who use manual wheelchairs as their primary means of mobility, and rehabilitation clinicians.

b) Define design criteria for the seat

Data from stakeholders was synthesized, analyzed and reviewed. Anthropometry data was analyzed to validate the targeted height adjustment range. From the collected information, specific design criteria were developed.

c) Conceptualize different design solutions

Design concepts for the adjustable height wheelchair seat were created using brainstorming, concept sketches and computer models. A “design matrix” was used to sort the brainstorming and research results. To better analyze the possibilities of engaging different mechanisms into design concept, a checklist with design criteria on it was created and used as guidelines to select the optimal design.

d) Fabricate prototypes

Selected concepts were fabricated as fully functional prototypes. These prototypes embodied most functions of design and interface layout.

e) Evaluate prototypes and revised designs as needed

Prototypes were initially evaluated against design criteria using simple operational and performance tests with non-disabled persons to assess safety and stability. Finally, wheelchair users were recruited to perform several tasks on the designed prototype. Throughout design iteration and user testing, design criteria continued to be modified with design trade-offs being carefully analyzed

f) Present finalized design

The final design resulted from multiple iterations resulting from testing. It has been developed using 3D models and rendering and reflects the optimization of material sourcing and use, as well as refinement of user interface. Also cost estimation was done with the documentation of possible material suppliers and manufactures.

CHAPTER 2

BACKGROUND AND CURRENT STATE OF THE ART

2.1 Current Products

A seat that enables a manual wheelchair user to transit vertically ±5 cm (2 in) from a standard seat height is not available on the market. Several products do exist that meet some of the targeted uses of the proposed device.

Power seat elevators are used for transfers or functional reach and are available from all the major manufacturers of powered mobility bases. Motion Concepts also offers three other power seat functions, the Uplift, Assist and Anterior Tilt systems, which specifically assist with sit-to-to stand transfers. None of these systems can be used with manual wheelchairs.

Manual standing wheelchairs are available that transit a user into a near standing position (Levo, Lifestand). A relatively new product, the Elevation™ manual wheelchair by Instinct Mobility (http://www.useyourinstinct.com/), raises the seat about 10 inches so the user is in a semi-standing position. It is not sold in the US. These chairs certainly offer functional advantage for changing postures throughout the day and facilitating access to higher objects. However, manual standing technology has achieved only limited acceptability due to expense, complexity and, in the case of full standing chairs, weight.

Portable sit-to-stand assist devices are typically marketed to help ambulatory persons rise from a chair (i.e., http://www.comforthouse.com/porlifcus.html). Use in wheelchairs is not advisable as they are not designed to be wheelchair cushions. Likewise they should not be used in combination with a wheelchair cushion since this raises the user's overall center of gravity and compromises wheelchair stability. Some manual wheelchair users rely on transfer boards to facilitate transfers. They are inexpensive and useful for certain users but must be carried around. Reachers are simple, inexpensive devices used to retrieve objects, but also need to be carried throughout the day and are not as effective as reaching with one's hands.

Options for lowering the seat of a manual wheelchair are even more limited. Hemi height manual wheelchairs or drop seats are available for people who use foot propulsion, but these chairs may hinder sit to stand transfers and overhead reach.

2.2 Patents And Other Prior Art

Several attempts have been made to design an elevating seat for manual wheelchairs. Prior art was investigated and references to seat height adjustment devices related to both wheelchair and non-wheelchair seats were found. U.S Patents database was the major resource for investigation of prior art. Key words such as "height adjustable seat" "wheelchair seat design" were used in the search. Prior art contains references to non-electrical seat height adjustment systems that may act as inspiration for the current design.

Toppses' design *"Wheelchair with Adjustable Seat"* (Toppses, 2002) is a wheelchair which has an adjustable seat that can be raised and lowered. The height adjustable seat was designed to enable a wheelchair-dependent person to gain access to the seat from ground level, independently raise him or herself from the ground level to the normal operating height, and reach things overhead more easily. The seat height is adjusted by rotation of the shaft in one direction, and the cables connected with shaft wind around the shaft to thereby raise the seat (Figure **4**).

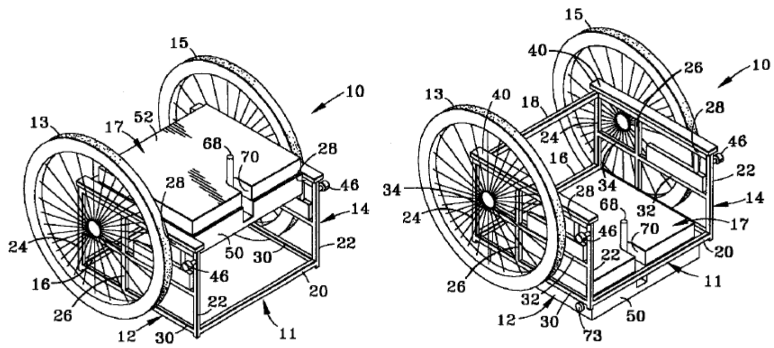

Figure 4: Wheelchair with adjustable seat

"Wheelchair with vertically adjustable seat" (Schlangen, 2000) explores the design of a height adjustable seat applying scissor frame mechanism as a lifting unit and a crank in front as the operation handle (Figure **5**).

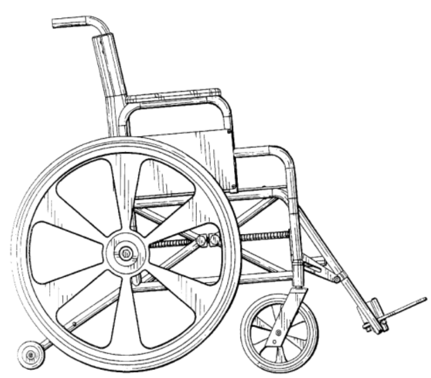

Figure 5: Wheelchair with vertically adjustable seat

“*Wheelchair Having A Double Turnbuckle Height Adjustment”*(Mascari, 2002) describes a manual system for adjusting the height of the seat via an in line turn buckle located under the seat. The device works by adjusting the spacing between the frame members. The device narrows the chair frame as the seat rises, which limits usability for users. The turnbuckle is not easy to reach while in the chair and provides little mechanical advantage (Figure **6**).

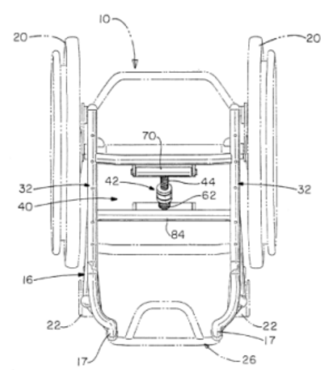

Figure 6: Wheelchair having a double turnbuckle height adjustment

“*Retrofit Height Adjustable Seat*”(Bell, 2009) shows A retrofit height adjustable seat for a chair. The lifting and lowering of seat is operated by retraction of two arms at each side of the seat (Figure **7**). Stop of the lifting of lowering is achieved by inserting and retraction of arm from a slot placed b side of seat. The biggest disadvantage or this device is that it only works when user is out of the chair.

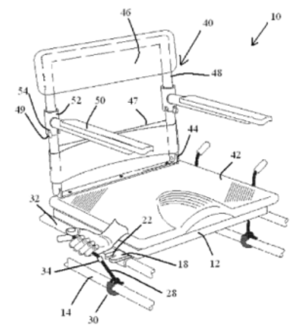

Figure 7: Retrofit height adjustable seat

One patent that controls seat height is using a telescoping vertical support(s). In *Seat Height Adjustment Device*" (Harper, 1973), the length of the telescope is controlled via a ratchet and clutch system. Alternatively, many patents refer to telescoping systems which are either gas/air assisted or spring loaded, which is commonly applied to office chairs or salon chairs. Those equipment mechanisms have fairly long unextended length, which may become obstacle for appropriate placement. These systems are advantageous because they can be adjusted with the user still partially seated.

Investigation into the prior art of general lifting device shows that a lot of methods have been explored to manually lift up a platform or seat. Both mechanical and pneumatic methods have been referenced in previous lifting device invention.

Lifting Device of the Scissor-Jack Type (Yanker, 1986) presents height adjustment application which utilizes two arms that are midway connected by a pivot. This scissor mechanism is used to carry up platform on top of it.

"Inflatable medical lifting Device" (Garman, 1997) introduces a means of height adjustment by using air inflation (Figure **8**). Based on the length of the hose connected to the bladder it may be possible to control such a system from both in and out of the chair.

The time required to adjust the height in such a system will be determined by the ratio of volume difference between air container and pump.

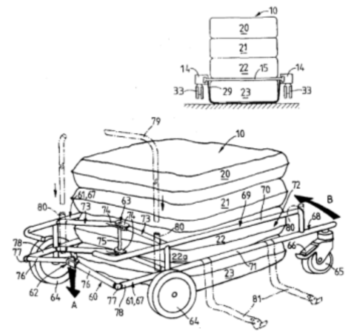

Figure 8: Inflatable medical lifting device

In addition to the seat height adjustment mechanism itself, prior art has revealed other considerations relevant to the current design. *Wheelchair Seat System* (Nordquist, 1991) describes a wheel chair seat base plate that is designed to fit on almost any chair (Figure **9**). The patent has revealed that if the preferred embodiment of the present invention is a retrofit design and not integrated into the chair frame, a similar universal mounting plate will need to be designed.

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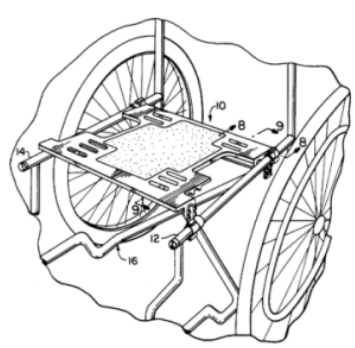


Figure 9: Wheelchair seat system

CHAPTER 3

DESIGN METHODOLOGY AND DESIGN INPUT

3.1 Approach

Research and design of height adjustable wheelchair seat design followed a User Centered Design (UCD) methodology. All the ideas and concepts were based on a thorough investigation and understanding of target users and possible design solutions. As the design process progressed, the engineering threshold and design tradeoff also impacted on selection of design concepts. The figure below indicates the three crucial aspects of determining the ultimate design solution for the specific purpose (Figure **10**).

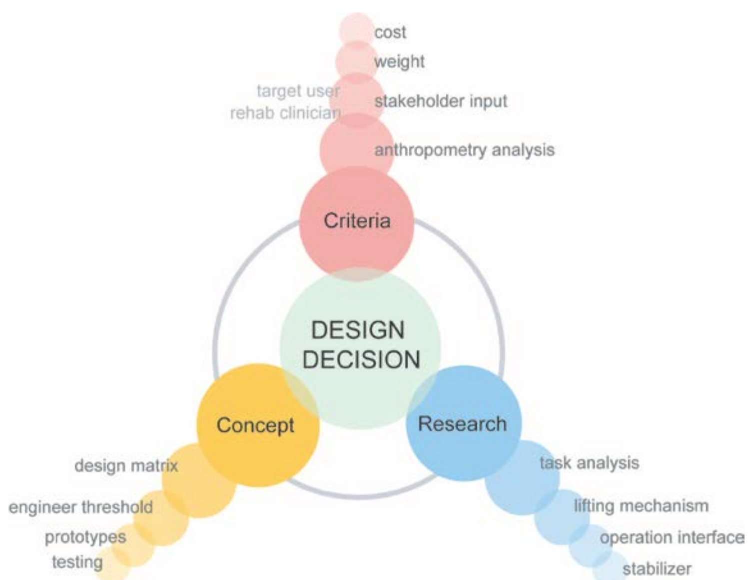


Figure 10: Strategy to look for ultimate design solution

In the proposed project, setting criteria required a series of tasks including analyzing anthropometry to figure out height adjustment range, conducting interviews with stakeholder groups to set a design goal regarding the weight and cost of height adjustment components. Within the research stage, different products on market were reviewed and categorized as a reference for design brainstorming. The products researched were of have different emphasis such as lifting mechanism, operation mechanism. User behavior and task analysis are also included in the research phase. It served as a prediction of users' activity and any potential risk within the design when users are interacting with height adjustment product. In the concept phase, all the brainstorming results were arranged into the design matrix; selected concepts were implemented as a prototype and tested. Final design decision was based upon iteration resulting from test and evaluation of design prototype.

3.2 Stakeholder Input

Two types of input were collected. A survey was deployed to wheelchair users to gage interest in and opinions about the concept. In addition, interviews were conducted with both wheelchair users and clinicians.

Stakeholder engagement covered many different issues, but a series of questions were defined beforehand that were posed to each cohort:

a) Should seat height adjustability be an add-on feature or incorporated into a dedicated wheelchair frame?
b) Is mechanical operation desired or are electrical components (and batteries)

acceptable?

c) Should seat height be adjustable when the person is not in the chair?

d) Is a height adjustment of +/- 5 cm (for a seat height range of 44-54 cm) adequate?

e) Should the seat height be infinitely adjustable or can height adjustments be realized by 3 distinct states (e.g., low, normal, high)?

f) Should the ‘high’ seat position also engage a wheel lock to enhance stability or would this adversely impact function?

3.2.1 Survey

Within a Human Centered Design class at Georgia Institute of Technology, an electronic survey was created using Survey Gizmo (http://www.surveygizmo.com/, 2005-2011). A link to the survey was sent to 159 individuals who were registered members of the CATEA Consumer Network and who identified themselves as wheelchair users. Thirty-four individuals completed all 19 questions on the survey (21% response rate) with three respondents being excluded from analysis because they did not report using a manual wheelchair at least part of the time. Of the 31 respondents, approximately 16% were younger than 40 years old and 84% were older. Nineteen respondents were male. Respondents ranged in years of experience in using manuals wheelchairs from less than one year to 57 years; their average experience in using wheelchair is 17.3years.

The survey included items about purchase preferences, living behavior, and financial situation in addition to the questions about the device. Over 56% of the respondents indicated that they lifted their wheelchairs into their automobiles independently. This suggests that weight of the wheelchair would be an important factor for an add-on component. When respondents were asked about the most important factor in purchasing a wheelchair, 41% of respondents indicated that durability was the most important factor. When asked about seat height adjustments, 39% of respondents indicated a preference for having a seat adjust higher only and 58% of respondents indicated a preference for having a seat adjust higher and lower. 47% of respondents indicated that two inches (approximately 10cm) were adequate and 53% said they want a large adjustment range. With respect to adjustment speed, 70% of respondents wanted the seat to fully adjust in less than 20 seconds. Additionally, wheelchair respondents expect the height adjustable seat to be incorporated in the wheelchair, comfortable, does not cause skin breakdown, and able to last for at least 5 years.

3.2.2 Stakeholder Interviews

Three group interviews were conducted with manual wheelchair users at the Center for Assistive Technology and Environmental Access, the Shepherd Center, and Parkview Manor Nursing and Rehabilitation Center. The nine participants ranged in age, experience using a wheelchair (3 months to 43 years), and physical constraints (incomplete quadriplegia, paraplegia, cerebral palsy, amputation, etc.). Seven of the nine participants were male.

Discussion focused on reaching and transferring as well as opinions on a height adjustable wheelchair seat. Although many interviewees did not consciously recognize the benefit to a seat height adjustable wheelchair, their reported difficulties in reaching and transferring indicated otherwise. Paris said that it “seems like a lot of things are an inch farther than my chair can go” (Paris, interview, 2/23/2010). “What is your reach like sitting in a chair?” Mike asked “It’s a lot like that” (Mike, interview, 2/25/2010). One interviewee reported that “19inch (seat and cushion) is enough to transfer to bed”.

Interviewees generally agreed that function for the seat height should be, but not required, adjustable when user is not in the chair. Considerations of durability, stability, and comfort must be included in design decision process. To be worth the possible cost it should be built to last. Participants also reported that alterations in height should not interfere with comfort, especially that of seat with body position should remain stable throughout this adjustment.

All of participants were concerned about time to adjust height. The shortest time mentioned was less than 5s, and longest acceptable time fell within the range of 30-60s.

One structure interview was done with 6 therapists in Rehab unit at Atlanta Medical Center. Four preliminary concepts were shown to the therapists and seven topics were covered during the interview. The preliminary concepts can be divided into two types of height adjustment: elevation and tilting (Table **1**, Table **2**).

Table 1: Concept evaluation I: elevation

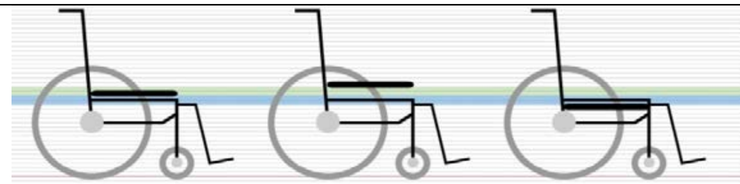
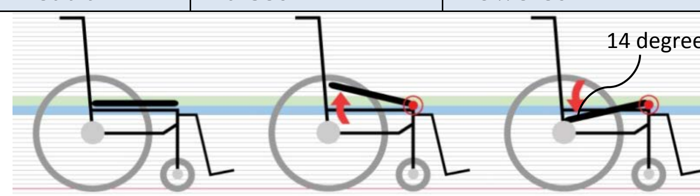
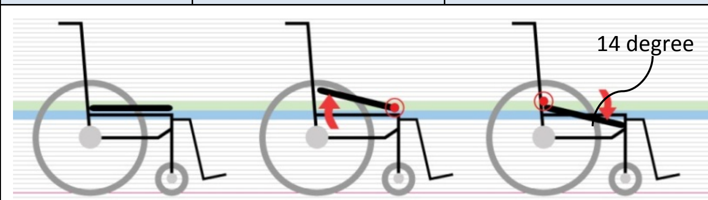
Concept Evaluation I: Elevation					
Concept		Description	Picture		
1	Elevation I	Only the seat surface moves up and down			
			Neutral	Raised	Lowered
2	Elevation II	The frame including back, seat, footrest move straightly together			

Table 2: Concept evaluation II: tilting

Table 2 Concept Evaluation I: Tilting					
Concept		Description	Picture		
			Neutral	Raised	Lowered
3	Tilting I	Single axis of rotation to tilt seat forward and rearward (rotation angle= 14 degree)			
			Neutral	Raised	Lowered
4	Tilting II	Multiple points or motion, the rear of the seat can elevate, the front of the seat can lower (rotation angle= 14 degree)			

3.2.2.1 Topic One: Considering The Usability And Safety Of Wheelchair User, Which Concept Do Participants Prefer?

All of the respondents agreed with elevation concept since tilting adjustment has significant risk of allowing the user to sliding down the seat. However, though concept 3 does not seem to lower the user's height when tilted down, it releases the pressure and helps user with standing up. The negative side is it needs extra efforts for user to sit back. So there are more problems in tilting concept.

Comparing concept 1 and 2, which were both within "elevation" category, therapist did not have very significance preference. Though most of them did not consider feet getting 2'' away from footrest make much difference from the neutral position, they pointed out that if feet are away from footrest too much, reaching things can be dangerous and problematic. One of the therapist thought it would be necessary to have the armrest go with seat height adjustment.

At last, 2 of 5 therapists expressed their opinion that a dedicated, seat-backrest-footrest moving system might be more likely to be used.

3.2.2.2 Topic Two: Which Height Adjustment Mechanism Is More Preferred, Mechanical Or Electrical?

None of the respondents gave instant feedback to this question; they came with further considerations in the respect of effort, cost and weight of the different mechanisms. Considering the effort aspect, some of them believed the effort needed to make the adjustment should be less or equals to that required to propel the wheel. When came to final decision, 2 out of 5 interviewees chose mechanical adjustment as a preference, 2 chose Electrical, 1 had no preference.

3.2.2.3 Topic Three: Add-On Unit VS Dedicated Chair?

One of therapist thought it would be good for the first time user to get a chair with dedicated function, but for those long term user who might be really used to their own chair already, the add-on function can be more convenient and cheaper.

Two out of 5 respondents supported the “add-on” idea since they believed the height adjustment function will not be needed permanently. Since wheelchair users are getting stronger and stronger during therapy, they might need to use this assistive function only during their hospital stay, but by the time they leave, would be strong enough to reach and transfer independently without height adjustment. It is possible that the add-on system could be equipment which belongs to hospital to assist therapy.

Two respondents preferred the “dedicated chair” idea since it is functionally safe and complete. They didn’t think it is possible to design an add-on component for all versions of wheelchair frames. So it is necessary for user who needs this function to completely switch to another chair. According to their experience, most wheelchair users do not notice the difference of wheelchairs, the best way for them to adapt to a new function is making them believe that function was there from the beginning.

3.2.2.4 Topic Four: Is automatic wheel locks necessary?

This function reminded some therapists of the “brake extension”, they consider brake extension is already useful enough and facilitate wheelchair with locking. So an automatic wheel lock is not necessary.

3.2.2.5 Topic Five: Height Control When the User Is Not In Wheelchair?

Inspired by this question, one therapist came with an idea that whenever patients left seat, it will automatically set back to neutral position or lower position, for the convenience of sitting back.

3.2.2.6 Topic Six: Allowable Weight of Adding This Functionality?

Respondents did consider the differences of added weight as on rigid frame or foldable frame. But generally they considered 4-5 lbs. add-on weight to be ideal. The “heaviest” mentioned by one therapist was 10 lbs.

3.2.2.7 Topic Seven: Discrete or Continuous Height Adjustment?

Discrete height adjustment means user can only reach certain number of height along adjustment. According to this design specification, the user can only reach three positions as 17.5’’, 19.5’’ and 21.5’’. A mechanism such as a cam design is specifically tailored to this type of adjustment. Continuous height adjustment has only two adjustment limitations, 17.5’’ as the lowest position and 21.5’’ as the highest position. User can stop anywhere between those two positions.

The neutral position along the height adjustment has an obscure height definition since this position is catering to different people’s preferences. People with different stature will have customized “neutral” position as their favorite and most convenient choice in doing daily activities. Locking a specific neutral position will exclude many users from getting the most comfortable position. The similar situation applies to car seat, which has a front to back adjustment. When the driver is adjusting the distance between sitting place and steering wheel, he has only two stops: the most front seat position, and the most backward seat position. A driver is able to learn and remember where the “preferred” position is located. This feedback suggests that a continuous adjustment can actually fit a larger user group’s preferences and it is more universal and accessible.

Combining the group interviews and web-based survey, the top concerns that most participants (including both wheelchair users and clinicians) identified concerning a height adjustable wheelchair seat height were: weight, stability, time/effort (ease of use), comfort, reliability, and amount of height adjustment.

3.3 Anthropometry Analysis

3.3.1 Anthropometry analysis for foot propulsion

Typically, a wheelchair can be ordered with a seat height of 17 ½’’ (44.5cm) and 19 ½’’ (47cm). The proposed design will allow the seat to be positioned at 17 ½’’ and extend to a 21 ½’’ height. To confirm the benefit of a low seat for foot propulsion, an anthropometry evaluation was performed to determine the percentiles of men or women able to sit on seats of varying heights and still be able to reach the ground to propel with one or both feet.

Human body dimensions were obtained by accessing the Civilian American and European Surface Anthropometric Resource Database (Caesar, 2004)and Kodak's

Ergonomic Design for People at Work(Chengalur, 2003) . Caesar Database reflects data from a sample of 4422 persons from the U.S., Italy and the Netherlands. Popliteal height, which refers to the distance from the underside of the foot to the underside of the thigh at the knees, is the corresponding measurement used for design of seat height. Thigh length refers to the distance from point of rotation at hip to point of rotation of knee. It is widely used for the design of seat depth, and in this project, it serves as a reference for calculation of thigh extension when the person moves forward in a seat to reach the ground.

Table **3** lists the mean values for men and women:

Table 3: Anthropometry data of different genders

Anthropometry data of different genders (cm)					
	Men		Women		Resource
	Mean	SD	Mean	SD	
Popliteal height in sitting position	44.6	2.5	41	1.9	Kodak's Ergonomic Design for People at Work
Thigh length	43.5	2.92	41.3	2.93	Civilian American and European Surface Anthropometric Resource

To define the percentage of the population who can adequately reach the ground to propel, two postures were considered, an erect posture and one in which the user extends a thigh to better reach the ground. While seat height and popliteal height are the primary influences, to reflect real-world situations, cushion height and shoe thickness are also factors. Cushion height should also be included into the total distance from user’s sitting surface to the ground. In this analysis, it was assumed that sitting on a cushion increased sitting height by one inch (2.54cm). Also, it was assumed that user's popliteal height is increased by 1cm due to shoe height at forefoot.

3.3.3.1 Sitting Scenario One: Erect Posture

For the person who can naturally put his/her foot on the ground when sitting erect in a wheelchair (Figure **11**):

Distance to reach ground (X) = seat height + cushion thickness – shoe height

Distance to reach the ground equals to the sum of the seat height plus cushion thickness, with a deduction of the thickness of the shoe (Table **4**).

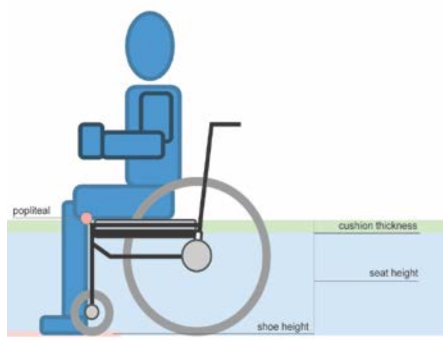


Figure 11: Dimension definition in sitting scenario one

Table 4: Distance to reach ground in erect posture

Distance to reach ground in erect posture (unit: cm)			
Seat height	44.45	46.99	49.53
Cushioning	2.54	2.54	2.54
Shoe	1	1	1
distance to reach ground	45.99	48.53	51.07

3.3.3.2 Sitting scenario two: Extended Leg Posture

For those who do not have the stature to reach the floor, one common technique is to slide forward and extend one's hip about 5 degrees as illustrated in Figure **12**.

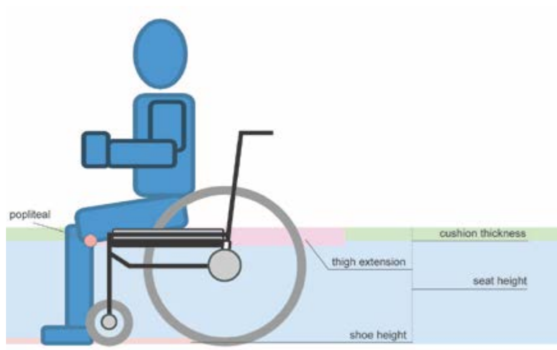


Figure 12: Dimension definition in sitting scenario two

The additional length of the lower limb can be calculated using thigh length collected from the Civilian American and European Surface Anthropometric Resource Database. The amount the thigh extension lowers the foot is dependent on thigh length and the degrees of hip extension which is estimated to be 5 degrees. The distance needed to reach the ground can be calculated as,

Distance to reach ground (X) =seat height + cushion thickness – shoe height –thigh extension

Thigh extension = thigh length * sin (5)

For both postures, the percentile of males and females who are able to foot propel the wheelchair can be estimated by comparing the distances needed to reach ground (Table **5**) with popliteal height anthropometry,

Table 5: Distance to reach ground in extended leg posture

Distance to reach ground in extended leg posture (units:cm)			
seat height	44.45	46.99	49.53
Cushioning	2.54	2.54	2.54
Shoe	1	1	1
thigh extension (male)	3.7845	3.7845	3.7845
thigh extension (female)	3.5931	3.5931	3.5931
distance to reach ground (male)	42.2055	44.7455	47.2855
distance to reach ground (female)	42.3969	44.9369	47.4769

To determine percentile, a "Z" value is calculated from the following formula:

$$\mathbf{Z=(X- \mu)/ \sigma}$$

In this formula, Z-score refers to the standardized value, X refers to the distance needed to reach ground, μ is the average popliteal height, and б is the standard deviation. By looking up the percentile value on a normal distribution graph, it can be found out the percentile of the population meeting the requirement (Table **6**).

Table 6: Percentile of men and women who can reach the ground in different scenarios

Percentile of men and women who can reach the ground in different scenarios						
Scenario 1: erect sitting stature						
	Men			Women		
Seat height (cm)	44.45	46.99	49.53	44.45	46.99	49.53
Z scores	0.56	1.57	2.59	2.63	3.96	5.30
Percentile that can reach floor (%)	28.90	5.80	0.48	0.43	0.004	
Scenario 2: sitting stature after sliding forward on seat						
	Men			Women		
Seat height (cm)	44.45	46.99	49.53	44.45	46.99	49.53
Z scores	-0.96	0.06	1.07	0.74	2.07	3.41
Percentile that can reach floor (%)	83.10	47.60	14.20	23.10	1.90	0.032

According to the table, in an erect sitting posture, 28.90% of male sand <1% of females are able to reach the ground when in a 17.5’’ height wheelchair. This percentile increases to 83.10% and 23%, respectively, after sliding forward on seat and extended a thigh. When in a standard 19.5’’ seat height wheelchair, only 6% of males and <1% of females are able to reach the ground from an erect posture , while 48% and 2% are able to do the same after sliding forward on seat.

The result indicates that a 17 ½” seat would permit a much greater percentage of the population to reach the ground and propel a wheelchair with one or 2 feet. However, the tradeoff is that a lower seat makes transferring much more difficult.

3.3.2 Anthropometry Analysis for sit-to stand transfers

Some wheelchair users need to complete a sit-to-stand maneuver when transferring out of the chair. The effort required to complete the task is determined by user’s weight and change in height of center of mass from the seated to standing postures. Seat height can impact the ease of performing a sit-to-stand transfer, therefore, an adjustable seat can be used to simplify this task for certain users.

This analysis calculated an estimate of the amount of work required to stand from different seat heights. The purpose was to document the benefit of rising from a higher seat and to inform the design about what vertical seat translation is necessary to lessen the effort of a sit-to-stand transfer.

Estimating the work required to stand requires calculation of a person’s center of mass in both seated and standing postures. Location of a person’s center of mass is related to person’s stature and weight in different postures. . Anthropometric data reports a person's center of mass when they are standing or seated. According to the data from Man-system Integration System(NASA-RP-1024, 1978), relationship between location of center of mass, weight and stature follows the formula of,

Location of center of mass [L (Z)] = [A x (stature, cm)] + [B x (weight, lbs.)] + [C]

Where L (Z) refers to location of center of mass from top of head (Figure **13**) and A, B and C are constants who values are found in the table below (Table **7**),

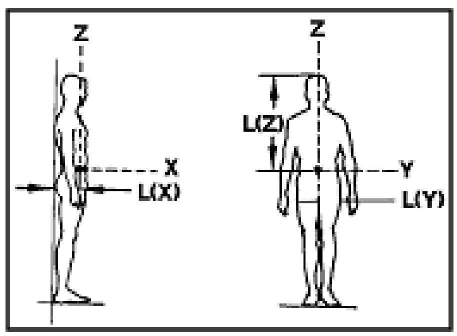


Figure 13: Whole body center of mass location of the American male crewmember

The height of the center of gravity can be calculated using the following equations:

In standing scenario, H= Stature – L (Z)

In seated scenario, H= Seat height – L (Z)

Table 7: Location of center of mass (cm)

	A	B	C	L (Z)			
				84% male	avg male	avg female	16% female
Standing	0.486	-0.014	-4.775	80.2	77.5	72.0	69.5
Seated	0.344	-0.004	7.327	68.8	66.6	62.5	60.6
Seated with arms hanging	0.355	-0.01	7.389	69.5	67.5	63.5	61.6

H refers to the location of center of gravity with referenced plane (Table **8**):

Table 8: Location of center of gravity in different sitting stature

H	84% male	avg male	avg female	16% female	Referenced plane
standing	100.9	97.0	90.1	86.6	from ground
seated	21.6	20.0	19.3	17.2	from seat
seated- arms hanging	20.9	19.1	18.3	16.2	from seat

The work required to complete a sit-to-stand action is the product of the lifted body mass and distance that it moves along vertical axis. In the equation below, “h” refers to the distance that the center of mass moves during a sit-to stand task, “W” refers to the total work done to complete the task. Body weight (“mg”) rose during the task, and is based upon the portion of the overall body mass that is rising when standing and includes the masses of head, trunk, upper extremities and thighs since the center of mass of legs are not moving during the task. Calculations are done to compare the work required to stand from 3 seat heights (17.5’’, 19.5’’ and 20.5’’), with 1’’ added to reflect the influence of a cushion, resulting in seated heights of 18.5’’, 20.5’’, and 22.5’’, for male, weight of head trunk, upper extremities and thighs takes up 88.6% of the whole body weight, while for women the percentage is 87.8% (Table 9).

$$\mathbf{h = H\ (standing) - [H\ (seated) + seat\ height]}$$

$$\mathbf{W = mg}$$

$$\mathbf{m = M * 88.6\%\ (male\ user)}$$

$$\mathbf{m = M * 87.8\%\ (female\ user)}$$

Table 9: Mass to be lifted during sit-to-stand task

User mass data				
	84% male	avg male	avg female	16% female
mass (M)	98.3	83.2	66.4	52.5
mass of head, trunk, upper extremities and thighs (m)	87.09	73.71	58.29	46.09

Based on the calculation, there is a significant decrease of work required to complete a sit-to-stand task when seat height is increased (Table **10**). This percentage of reduced effort goes up as the user's weight decreases. For example, for a seated height of 20.5'', an average weight female is expected to save 42.59% of the work required to raise from an 18.5'' seated height, while average weight male saves 33.8%. It also indicates that the higher the seat, the less energy it requires completing sit-to-stand task.

Table 10: Comparison of work by using different seat height wheelchair to perform sit-to-stand task

Distance CG (center of gravity) is lifted from sit to stand (unit: cm)				
	84% male	avg male	avg female	16% female
18 1/2 seat height	32.26	30.06	23.85	22.40
20 1/2 seat height	27.18	24.98	18.77	17.32
22 1/2 seat height	22.10	19.90	13.69	12.24
Work required from sit to stand (unit: joule)				
18 1/2 seat surface height	275.61	217.40	136.43	101.29
20 1/2 seat surface height	232.21	180.67	107.37	78.32
22 1/2 seat surface height	188.81	143.93	78.32	55.35
Percentage of reduction in work by elevating seat above 17 1/2" (or 18 1/2 with cushioning)				
seat surface height= 20 1/2	15.75%	16.90%	21.30%	22.68%
seat surface height = 22 1/2	31.50%	33.80%	42.59%	45.36%

3.4 Design Criteria

Based on the result from stakeholder input and anthropometry analysis, design criteria were listed to inform the design concept and prototype. Some of the criteria are considered to be essential part of the design, marked as “Required”. Some of them, which have the possibility to be revised and adjusted based on design implementation, were marked as “Targeted”.

a) Required criteria: The seat-to-floor height adjustment is ranging from 17 ½’’ to 21 ½’’, with the neutral position of 19½’’high.

There are three stages during the adjustment: lowest position (17 ½’’), neutral position (19½’’) and highest position (21 ½’’).

b) Required criteria: The seat height adjustment is vertically up and down, seat surface remains horizontal during the adjustment.

Change in seat height will be done in a manner that does not alter the seated posture of the user. Seating pressure can remain constant during the elevation.

c) Required criteria: The seat height adjustment unit can fit into a manual wheelchair seat frame with the width of 18’’ and depth of 16’’.

18’’by16’’ is a typical adult wheelchair seat size. The adjustment unit should not increase the width and depth of wheelchair.

d) Required criteria: The seat height adjustment should support a user that weighs up to 250lbs.

The add-on height adjustment function should not affect a standard wheelchair’s weight capacity, which is 250lbs.

e) Required criteria: Wheelchair user can maintain stability at any height during height adjustment.

User should not have any potential feeling of tipping or falling in either direction when he/she has reached the maximum height.

f) Targeted criteria: The seat height adjustment control needs to be operational while not in the chair.

Accessible adjustment when user is not in the wheelchair would ease transfer into a chair from another location.

g) Targeted criteria: The seat height adjustment unit should weigh no more than 5lbs.

Considering that most manual wheelchairs weigh about 30-35 pounds so this additional weight represents a 14-17% increase

h) Targeted criteria: Wheelchair user is able to make the height adjustment by one hand independently.

Two-hand-control requires more exercise and action consistency, which could be hard for wheelchair users. Occupying both hands also reduces the balance of the user.

i) Targeted criteria: It takes no more than 20 seconds for user to reach either maximum high or the maximum low setting.

According to the survey results, acceptable time for height adjustment varies for different users, 5s-30s was the time range preferred by most stakeholders.

j) Targeted criteria: Manufacture cost of the retrofit unit should be less than $50.

The wholesale price of a standard K0001 wheelchair is between $125 and $175, the add on manufacture cost should be targeted at less than 30% of wheelchair’s cost to a supplier.

k) The seat height adjustment can be achieved either by mechanical or electrical mechanism.

The power method will be decided based on trade-off comparison and evaluation concerning weight, size and energy consumption factors.

CHAPTER 4

PROTOTYPE DESIGN, FABRICATION AND EVALUATION

4.1 Prototype Design

This design phase included brainstorming, concept sketches and computer models. By categorizing and investigating different mechanisms used for height adjustment, a “design matrix” was created to tabulate brainstorming and research results. Design concepts were selected based on the design matrix. Models were created and rendered in 3D software to visualize different design concepts.

4.1.1 Resource Browsing

The lifting system is comprised of three primary components. The most important part is the “lifting force”, which provides the main strength in height adjustment. Two kinds of lifting mechanisms were investigated in this research, mechanical and pneumatic. The representative of mechanical lifting includes scissor jack, four bar linkage etc. while pneumatic lifting devices included bladder, air bellow etc.

The second primary component is the operation interface. Different control methods were considered for the different lifting methods. Certain control methods are compatible certain mechanisms, while some are limited to other mechanisms.

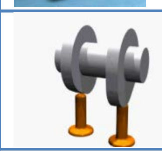
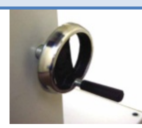
The third component is a stabilizer, it was initially assumed to be an optional component at early stage of design, since some lifting mechanisms have embedded stabilizing mechanisms. Some lifting mechanisms, such as air, only provide lifting force, making the stabilizer a requirement.

Design Matrix is a method to help inspire designers during brainstorming and innovation. It is a sorting and categorizing process of all the related design ideas. In this design project, a design matrix was developed for all three components: lifting mechanism, handle/operation, and stabilizers. Since the choice of stabilizer is very dependent on the concept design, it was considered to be used for prototype refinement and improvement. For the preliminary design concept, the “lifting mechanism options” and “handle/operation options” were considered to be the most effective tool in facilitating this think-aloud process.

The following two tables were the result of categorizing lifting mechanism and operation options (Table **11**). To better document the information, all the items in “lifting mechanism option” table were marked with alphabet, while items in “Operation interface option” table were marked with numbers.

The lifting mechanism options include devices used to adjust length or height, whether by manual or power. Each lifting mechanism has an operation interface to match application. The “Operation interface table” divided the operation interface into two categories, one compatible with mechanical lifting units, and the other category includes those compatible with pneumatic products.

Table 11: Lifting mechanism and operation interface options

Lifting mechanism options					
	Mechanism	**Picture**		**Mechanism**	**Picture**
A.	Scissor jack		B.	4-bar linkage jack	
C.	Salon Plumb		D.	450 Lb. Capacity Transmission Jack	
E.	Pneumatic bladder or bellows		F.	Laboratory scissor jack	
G.	Electrical Linear Actuator		H.	cam	
Operation interface options					
	Mechanism	**Picture**		**Mechanism**	**Picture**
Mechanical					
1.	Crank		2.	Ratchet	
3.	Wheel		4.	Button control (power only)	
Pneumatic					
5.	Bulb Hand pump		6.	Miniature pneumatic pump	
7.	One-way/ Two-way hand pump		8.	Button valve	
9.	Butterfly valve		10.	Globe valve	

4.1.2 Mechanism and Application Review

In the case of height adjustable seat wheelchair design, the designer was not going to “invent” a mechanism. Instead, finding existing tools with height adjustment feature would be a smart way to achieve the final function. There are numerous existing tools used for lifting heavy things. A significant number of examples can be found on car seats, vehicle jacks, power wheelchair seats, office chairs, adjustable workstations etc. Some of those mechanisms require manual operation only, while some require electric power. A documentation regarding different height adjustment methods was collected through more than two-month period of research and investigation. Each application mechanism was evaluated based on the design specifications such as size, self-weight, capacity, operation time, adjustment range, maintenance and cost.

4.1.2.1 <u>Mechanism I: Scissor Jack</u>

In the case of height adjustable seat wheelchair design, the goal was to find an existing tool to achieve the final function. There are numerous existing tools used for lifting, including car seat lifts, vehicle jacks, power wheelchair seats, office chairs, adjustable workstations etc. Some of those mechanisms require manual operation, while some require electric power. Different height adjustment methods were identified through a two-month period of research and investigation. Each mechanism was evaluated against the design specifications using size, self -weight, capacity, operation time, adjustment range, maintenance and cost.

4.1.2.2 <u>Mechanism I: Scissor Jack</u>

The term "scissor jack" describes a wide variety of tools that all follow the same principle: using crossed beams to lift something. Its folding capability allows the user to store the jack when it is not in use (with the diagonal beams flat) and to expand it when it is needed (Figure **14**).

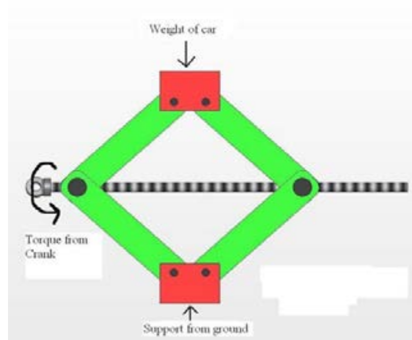


Figure 14: Illustration of scissor mechanism

Scissor lifts are all built in symmetrical shapes. In order to work, the distance from the loaded point to the cross point must be the same as the distance from the cross point to the ground. This ensures that weight is distributed equally throughout the scissor lift beams.

Since scissor lifts have such a wide variety of use, they also have a wide variety of power sources. They can be powered or operated manually.

Scissor lifts basically fall into two categories: single scissor lifts and multiple scissor lifts. A single scissor lift has just two crossbeams and one "x." This means it can only go so high because the length of the crossbeams restricts the height of the lift, and making them too long would make it both unstable and unwieldy.

The rate of height adjustment in a scissor jack is non-linear. According to this graph indicating the motion principle of scissor jack (Figure **15**), the vertical height change Δ**H** is different when X represents different angle. The graph and formula below shows the calculation of Δ**H.**

H=a*sin(X+10)-a*sinX,

Where a is the length of the scissor jack arm, X is the angle of the arm to the horizontal, and ΔH is the change in height from an angle X to the angle X=10 degrees

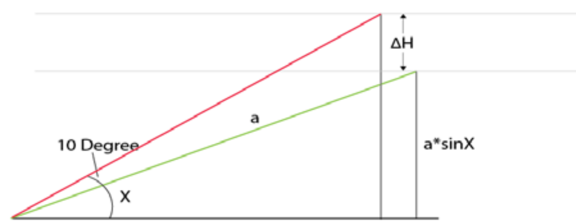


Figure 15: Motion principle of scissor jack

Using a scissor jack arm of 8’’ results in the equation,

ΔH=8*sin(X+10)-8*sinX

This equation shows that a 10- degree change in angle will result in a greater ΔH if X is small. For example, if the scissor arms start horizontal (X= 0°), a 10° change results in ΔH=1.4”. However, if the starting angle of the scissor jack is 45°, a 10° change in angle results in ΔH=0.9”. From a design perspective, a scissor jack must be configured to start at a small angle to change height rapidly. In other words, the rate of height adjustment in scissor jack is never constant (Figure **16**).

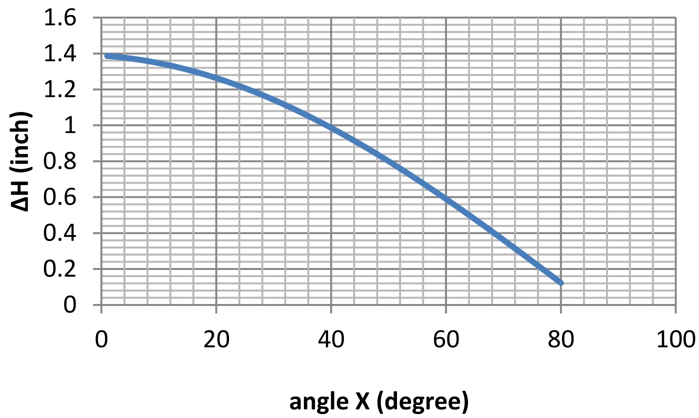


Figure 16: Relationship between ΔH and change of angle

Application I: Manual Scissor Jack

A commonly used vehicle scissor jack (Figure **17**) quickly changes height from 3 3/8’’to 15 1/8", covering an adjustment range of 11 ¾’’ It is able to handle up to 1.5 tons weight, which is far more than the required weight capacity of height adjustable wheelchair seat design. This scissor jack requires 20 rotations of handle operation to get a height adjustment of 4’’.

Figure 17: Manual scissor jack

Scissor jacks are usually made of heavy duty steel construction for strength and durability. Most of them weigh around 10lbs, but some with special design of the material can reduce their weight to around 6lbs. To speed up the lifting mechanism, usually a speed-bar is included to facilitate user with implementing height adjustment.

Application II: Power Scissor Jack

Electrical car jacks are an example of powered scissor jack application. It is most commonly powered by vehicle's lighter plug. An electrical car jack set is composed of a scissor jack, a motor and a lighter plug (Figure **18**). It is able to lifts most vehicles over 10'' in 40 seconds and has a maximum loading capability of 2000 lbs. vehicles. Usually an electrical scissor comes a color coded handle bar with convenient super bright LED light on it, which is very helpful for night time use. The total amount of weight of the jack set is around 9lbs and it has a height adjustment range of 9 inches. Market cost of the cheapest electric scissor jack is $60-$120.In order to work properly, an electrical scissor jack usually requires a working voltage of 12V, with max current as 10A. The power was set to automatically stop the jack if load exceed max capacity.

Figure 18: Electrical scissor jack

Application II: Lab Jack

Lab jacks are also a common scissor jack application in labs and class (Figure **19**). It is ideal for supporting or elevating beakers, flasks, water baths, stirrers, and other lab equipment. Usually, a lab jack is made of high strength steel and it usually has an adjustable height ranging from 3" to 10.5". What is accessible for lab jack design is that it usually has oversized knob allows for quick and easy adjustment. A lab jack with 8’’by 8’’ plate size is able to lift up to 200lbs product. Lab jack’s self-weight varies from 3lbs to 15lbs depends on the material.

Figure
19: Laboratory scissor jack

Advantages VS Disadvantages

There are both advantages and disadvantages to apply scissor jack mechanism to the height adjustable wheelchair seat design. In the manufacture aspect, the benefit of this mechanism is that it is simple to manufacture. In terms of function, it is easy to adjust the height range by using different screws to generate different torque. In the user operation aspect, it is an easy action for common user to rotate the bar-handle, but for wheelchair users who may lack hand dexterity, the rotating of bar handle may be a disadvantage. Self-weight is also a problem when using the same material as scissor jack, since to get enough strength for support; the scissor jack usually uses heavy duty material which makes the application itself really heavy.

4.1.2.3 Mechanism II: *Motorcycle center stand*

The motorcycle center stand is used to lift a motorcycle off the ground for maintenance, oil and part changes, or storage, it is completely manual operation applying heavy-duty cross-link lifts system with a combined mechanisms of threaded lift bar and pivot plate (Figure **20**). With a 2"wide lift platform, the adjustable lifting height of this mechanism is from 5" to 9". But instead of being lifted straight up, the lifted surface will result in being moved for certain distance forward after lifted up.

The lifting mechanism applied by motorcycle center stand, a four-bar linkage set, requires an even/level frame to work properly. It usually requires socket and ratchet/wrench for operation, which would be a very big barrier for the use by wheelchair users and it may also slow down the operation time. This product usually made of heavy-duty steel, has a self-weight of 13- 20lbs, and lifting capacity up to 1,500lbs, which is far more than the design criteria requires.

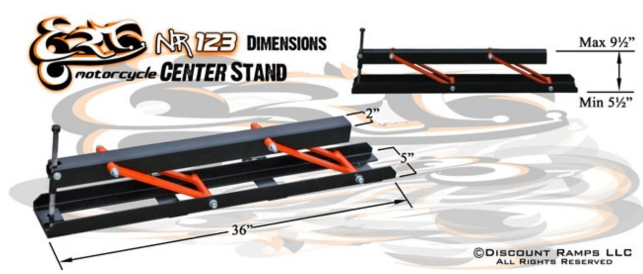


Figure 20: Four-bar linkage motor jack

4.1.2.4 Mechanism III: Linear Actuator

A linear actuator is operated by a source of energy, usually in the form of an electric current, hydraulic fluid pressure or pneumatic pressure, and converts that energy into some kind of linear motion. Mechanical and hydraulic actuations are the most common methods of achieving the linear motion.

Figure 21: Electrical linear actuator

The figure (Figure **21**) shows an example of a mini linear actuator with 4" stroke and installing size of at least 8’’. It uses a 12V / 24V DC permanent magnet motor, and has a 165 lbs. of max pushing weight capacity. Different levels of speed can be adjusted to 0.39", 0.63", 0.79", 0.94", and 1.14" per second, which means the shortest time it will take to lift from the lowest position to highest position is less than 4 seconds.

Application: Power Wheelchair

Linear actuators are widely used in power wheelchair to achieve the function of seat height adjustment. There are different sizes of linear actuators used to get this function. A wide range of movement can be achieved by actuator, and some of power wheelchairs have a height adjustment of over 10’’. Most of Permobil’s Rehab Series wheelchairs have the function of seat elevator. (Permobil, 2011) Take the C300 Corpus for example (Figure **22**), it uses a very big actuator and is able to move the seat up and down for 8’’.

Figure 22: Permobil C300 Corpus power wheelchair

Advantages VS Disadvantages

Linear actuators provide a very smooth and stable movement of height adjustment, and also provide the possibility to design a better user control method for the convenience of most wheelchair users. However, the cost of both power wheelchair and linear actuator are significant. The cheapest linear actuator which has 4’’ adjustment will cost over $60, which is a large amount of money compared with a common manual wheelchair. Also there is a problem with the weight of actuators. Since actuator cannot work without electric power, it is required to have a battery go with the installment of linear actuator. The battery also accounts for extra weight which will make the add-on design heavier. The extra maintenance of battery is another issue with this application. If the add-on design is going to be used on manual wheelchair only, it is doubtful about the necessity to have costly maintenance just because of the height adjustment feature only.

4.1.2.5 Mechanism VI: Gas Spring

A gas spring is a type of spring that, unlike a typical metal spring, uses a compressed gas to exert a force. It is basically a system consisting of a pressure tube, rod and piston. The energy for the spring is provided by gas at high pressure and the whole system is self-contained and sealed against loss. Gas springs are used in automobiles, where they are used to support the weight of doors while they are open. They are also used in furniture, medical, and aerospace applications.

Application 1: Office Chair

In an example of the widely used height-adjustable office chair (Figure **23**), a pneumatic gas lift is applied for the seat height to be adjusted in a range of 19.5’’ to 23’’. It can also support a weight rated up to 250lbs, with the supporting surface dimension as 20’’ depth and 20’’ width. There is an upright locking position function in the office chair, enabling user to stop in anywhere between the highest and lowest position.

Figure 23: Height adjustable office chair

Application 2: Sit-stand wheelchair

The Levo LAE manual wheelchair provides the alternative to adjust body position from flat sitting to complete standing position up to 85° (Figure **24**). With the help of gas spring, which move user to controlled positioning through easy one hand operation, this wheelchair enables user to stay in any position between sit and stand with optimal and matched body mechanics in all seating and standing positions.

Another function of gas pipe is to facilitate the movement of linear actuator, in order to reduce the cost on actuator as well as balance the movement. There is wheelchair design applying the combination use of two gas pipes with the linear actuator in the middle. The linear actuator performs the main propelling force with gas springs assisting. The three columns can distribute the force properly and maintain the balance of movement.

Figure 24: Levo LAE standing wheelchair

Advantages VS Disadvantages

Similar to linear actuator, gas spingss also provide a very smooth and stable horizontal movement in most of its application, and it does not require any battery or extra maintenance. One limitation with proper work of a gas spring is that it requires weight to be taken off from the seat when releasing the pipe. Which means, at the time that user wants to have the seat elevated, the user should be able to lift himself away from the seat. It is a very difficult and energy-cost task for most elderly wheelchair users, who will be the majority user of the proposed design.

4.1.2.6 Mechanism V: Cam

A cam is a rotating or sliding piece in a mechanical linkage used especially in transforming rotary motion into linear motion or vice-versa (Figure **25**). Usually it is a part of a rotating wheel (e.g. an eccentric wheel) or shaft (e.g. a cylinder with an irregular shape) that strikes a lever at one or more points on its circular path. The cam can be a simple tooth, as is used to deliver pulses of power to an eccentric disc or other shape that produces a smooth reciprocating (back and forth) motion.

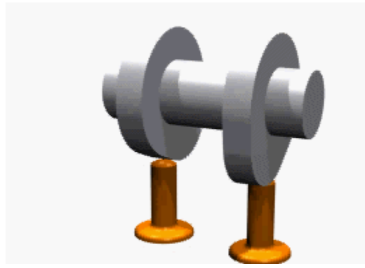


Figure 25: Cam

The cam mechanism is good for small linear movement. Examples can be found on accurate devices such as watch components and locks. The benefit of cam is that it creates a very simple movement to achieve the height adjustment. Also, the cost of this mechanism is rather low, and it does not require any extra maintenance. However, no examples of using cams to lift body weight were found, it is unclear how much force would be required to lift the user himself up and down. Other challenges of using a cam mechanism include to the need for small size of components, the possibility that multiple cams would have to move simultaneously. If multiple cams are placed under the seat, a proper linkage would be required to link them together. Finally, a cam design might require both arms to operate and not all users may have adequate strength in both arms.

4.1.2.7 <u>Mechanism V: Pneumatic Lifting</u>

The concept of using an airbag as a lifting source comes from pneumatic lifting in healthcare and emergency support areas. There are various ways to inflate a bladder including manual and electric pumps. Operation of manual pumps is pretty simple and easy. The design challenges lie in inflating the bladder with enough air pressure and surface area to lift a person and to limit the required volume to allow for manual inflation. Therefore, the design sought to seek a compromise between required pressure, and volume which is related to the bladder area.

To lift a 250 lbs. person, the surface area (A) required can be calculated from the following equation.

$$\mathbf{A} = \frac{\mathbf{F}}{\mathbf{P}}$$

Where F is body weight and P is bladder pressure. The air bladder requires a height of at least 4 inches to be able to adjust seat height by that amount. So, the volume of the bladder depends on this height multiplied by the surface area. Using a goal to keep bladder pressure under 4 PSI, the following calculations were made to determine required surface area. For P=3 psi, the area needed to support a 250lbs person is 83.39 sq. inch and for P=4 psi, the area needed to support a 250lbs person is 62.62 sq. inch,

Application 1: Bladder

Bladders are commonly used in many kinds of equipment. They are light and can be inexpensively made. Bladders are typically made from materials that are resistant to many chemicals. The one shown in the figure below is made from polyurethane (Figure **26**). Edges of the bladder are heat sealed to prevent air leakage. A small opening is allocated on verge of the bladder surfaces to seal the valve. Tubes can be extended from the valve and connected with pumping equipment.

Figure 26: Pneumatic bladder for health care

Application 2: Bellow

Another kind of pneumatic lifting application is bellow, a deformable container which is designed to compress in a repeatable manner (Figure **27**). When pressed, the bellow delivers pressurized air in a controlled quantity to a controlled location. As the volume of the bellow is decreased, air escapes through the outlet. The air bellow provides a wise solution to transfer air, usually it is pumped either by hand or foot. The volume of bellow varies a lot due to different application, for a hand held size, the volume is around 5L, flexible and smooth materials such as polypropylene is most common for the manufacture. Due to the size and operation benefit, bellows can either be a good lifting or pumping device.

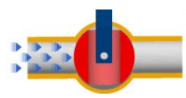
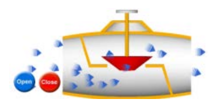
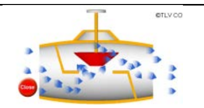
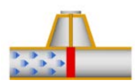
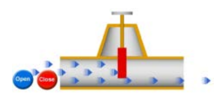
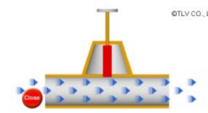
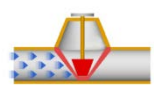
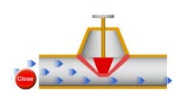
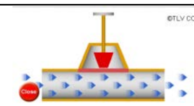
Figure 27: Hand pumped bellow

Related Device: Valve

A pneumatic lifting device will require a valve to control the flow of air. There are four main valve designs (Table **12**). In the first type category of valve, the valving element body 'rotates' in the passageway to stop flow. Typical products within this category include ball valve, butterfly valve. The operations of using this kind of valve are simple switching actions such as turn on or turn off, usually using a lever mechanism. Within the second category of valves, the valving element acts as a 'seal or a plug' in the passage way to stop flow. From the outside, this kind of valve appears to have a movable disk-type element and a stationary ring seat in a generally spherical body. A globe valve is a typical example of this valve type. In the third category, the valving element is 'inserted' into the passageway to control flow. A gate valve, also called sluice valve, is the most common product in this category. The distinct feature of a gate valve is that its sealing surfaces between the gate and seats are planar. Gate valves are often applied when a straight-line flow of fluid and minimum restriction is desired. A diaphragm valve represents the fourth mechanism, within which the valve's passageway itself is 'pinched from the outside' to stop flow. Diaphragm valves are also called membrane valves, because they consist of a valve body with two or more ports, a membrane, and a "saddle" or seat upon which the membrane piece closes the valve. It is constructed from either plastic or steel.

Manual operation of valves can be done in different manners. Lever and push button are common operation methods. A lever is usually connected with ball valve. A crank or wheel is usually connected with a globe or gate valve. A push button can also be applied to valve operation, including a button press and spring return.

Table 12: Different valve types

	Valve closed	Valve half open	Valve fully open
Ball valve/ Butterfly valve			
Globe valve			
Gate valve (sluice valve)			
Diaphragm valve			

Related Device: Pump

A pump is a device used to move fluids, such as liquids, gases or slurries. Energy is required to move air outside the pump into the pump body, and propel it through tubes or pipes. Several types of pumps are available for a user to operate manually. For a balloon pump, the action is pushing and pulling the handle, while for the bulb pump, this action is to squeeze the bulb. A bellows pump requires a straight force from top either by hand or foot. Pump volume determines how much air is moved during one stroke. A larger pump volume requires more effort and energy**.** However, there is always leakage between the connections of different parts, which influence the efficiency of user's task.

Advantage and disadvantage

The most significant benefit of using air as lifting force is the weight advantage. Both bladders and bellows can be made of very light and thin material. The air inside does not account for any weight at all. Then second benefit of air lifting products is the cost, especially when put into mass production. According to market research, the retail price of a 13'' (L)*6'' (W)*5'' (H) bladder is $25. A 5L air bellow with foot pump is usually around 16$. This combined coast of bladder and pump is consistent with the target price of the adjustable seat height system.

However, the disadvantage of using air as a lifter is achieving stability. The flowing and floating nature of air makes the lifting surface very unstable when the air container is not fully inflated. So it is essential to include a stabilizer as air is doing the inflating work.

4.1.3 Design Matrix

A design matrix (Figure **28**) was laid out based on the resources documented in the tables (Table **11**). The columns were marked with alphabets, representing the content from "lifting mechanism option" table. The rows of matrix were marked with numbers, representing content from "handle option" table.

Handle \ Lifting Mechanism	A	B	C	D	E	F	G	H
1	A1		C1	D1		F1		
2	A2		C2	D2		F2		H2
3	A3	B3	C3	D3		F3		
4	A4		C4	D4			G4	
5					E5			
6					E6			
7					E7			
8					E8			
9					E9			
10					E10			

able to be prototyped

able to be prototyped, but doesn’t meet lifting design criteria

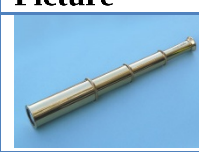
against current technology and not able to be prototyped

Figure 28: Design matrix

So the matrix is divided into 80 squares. Each square represents a possible design solution from a combination of certain lifting mechanism and handle option. But not every combination is able to be prototyped, so three different colors were used to fill the matrix and indicate whether this solution is scientifically achievable of not. Red indicates that the referred solution is not able to be achieved, due to limitation of current engineering technology. Nude color indicates that referred solution is able to be prototyped, but the final effect would not meet the requirements of proposed design. For example, the four-bar linkage mechanism could be driven by crank, wheel or ratchet. But height adjustment did not follow a vertical movement, which might impose potential risk on user's task. So no further investigation would be made into solutions using a four-bar linkage from this point. Green indicates that this solution was worth trying in a sketching or digital model.

An investigation into possible types of stabilizing mechanisms was also conducted. Information relating to various stabilizing application was collected and documented in a similar chart as the lifting mechanism. Since there was no guarantee of stability and balance just by randomly combining the lifting mechanism and handle to build a new lifting unit, a separate stabilization (Table **13**) part was required to be fit into the new design. However, as there were numerous kinds of stabilizing unit with various size and weight, the selection of this part was highly dependent on design of basic lifting structure. Therefore, the stabilizer options were not arranged into matrix. But the design chart was created for reference in the prototyping implementation stage.

Table 13: Stabilizer option

Stabilizer Option					
	Mechanism	**Picture**		**Mechanism**	**Picture**
i.	Drawer Slider		ii.	Telescopic cylinder	
iii.	Soft Buffer e.g. foam, rubber		iv.	Flanged linear motion ball bearing	
v.	Scissor frame				

4.1.4 **Concept Creation**

Multiple concepts were generated from the research and analysis of different mechanism options. Computer Aided Design (CAD) software permitted visualization of the different design concepts.

At the first stage, a universal platform was designed to fit on wheelchair frame, as the base for all the retrofit height adjustable components. The platform was made of an “H” shape 3mm aluminum painted plastic sheet, as well as four 3’’ height drop hooks. Since the design was targeting for both rigid frame wheelchair as well as cross frame chair. The platform designed could be fit on both of those two chairs. A K0002 cross frame wheelchair (Figure **29**) and a Zippie rigid frame chair (Figure **30**) were used as test chairs. Within the universally designed plate, the platform and drop hooks were commercially available.

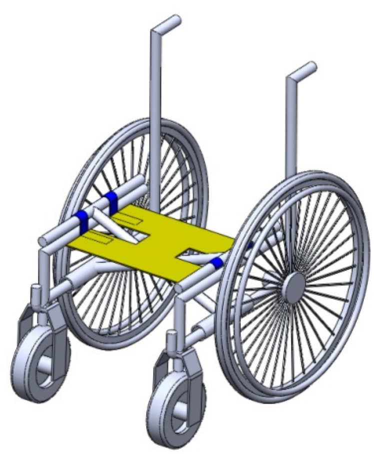


Figure 29: Platform on K0002 wheelchair

The universal platform provided a platform to experiment with different design possibilities. A variety of design concepts were proposed labeled with a combination of numbers and alphabets appearing in design matrix.

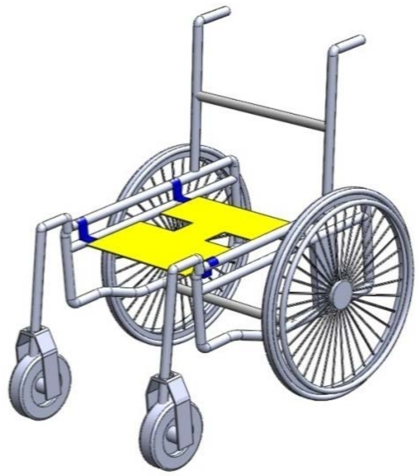


Figure 30: Platform on Zippie wheelchair

4.1.4.1 <u>Concept A1: Scissor Jack + Crank</u>

This basic design concept is a simple combination of crank scissor jack mechanism. It can achieve the basic functionality of height adjustment design (Figure **31**). All the components would be made of aluminum to reduce weight. When the user is adjusting the seat, a handle is pulled out to reduce the effort needed in rotating the crank. When the mechanism is not in use, the handle can be hidden under the seat so that it won't interfere with user's activity.

This mechanism is simple and achievable. The under-seat handle position is not convenient for some users and, it requires a fair amount of effort to rotate the handle.

Effort can be reduced by using a larger crank or wheel, but it results in the need for greater clearance to permit 360° of rotation.

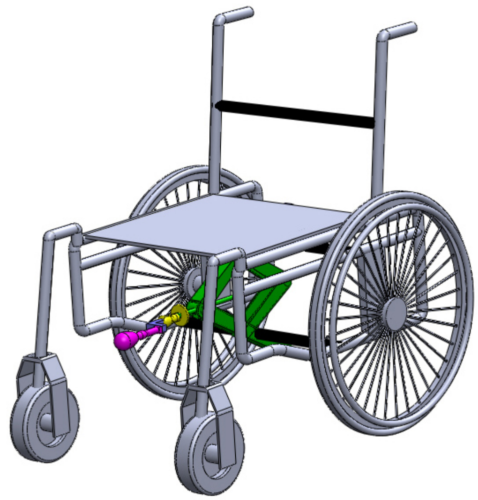


Figure 31: Manual scissor jack with crank handle

4.1.4.2 Concept A2: Scissor Jack + Ratchet

This concept is based on manual scissor jack with ratchet operation (Figure **32**). The user will utilize upper body strength to operate the ratchet handle in order to achieve height adjustment. The ratchet permit operation over a smaller range so more options for handle location exist compared to the crank design. The ratchet has only one direction "engaged", and a small buckle is in charge of adjusting the engaged direction. As the user is rotating ratchet in one direction, wheelchair seat lifts up. As the user turns the buckle to another side, seat lowers down when user is rotating ratchet handle in the same direction.

One weaknesses of the concept design is the single point of contact between seat and scissor jack; this may cause instability. A second weakness is that the ratchet direction must be manually changed to permit the user to reverse directions.

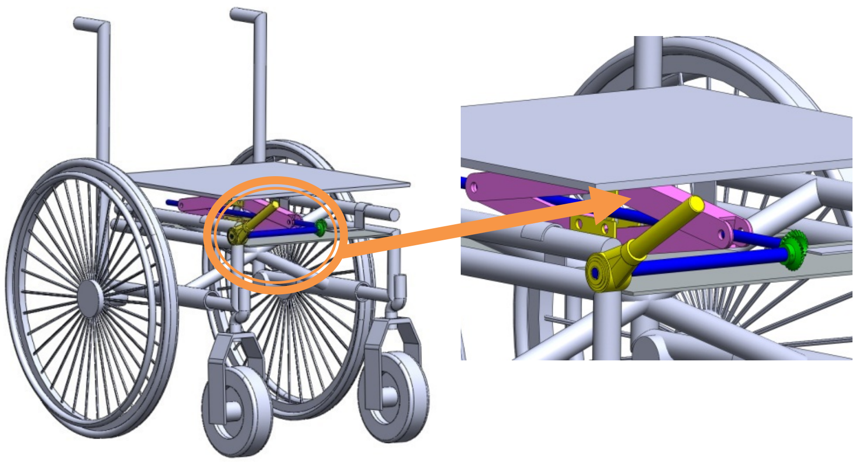


Figure 32: Manual scissor jack with ratchet handle

4.1.4.3 Concept A4: Powered Scissor Jack

In this design, an electrical scissor jack was fixed between seat and platform. The design allows for the elimination of a control handle to a simple push button switch (Figure **33**). A plate on top of the scissor jack was added to distribute the pressure as well as keep seat surface balanced during height adjustment.

As the scissor jack is able to support up to 2 ton weight, there is no problem with lifting up a person. As user presses up arrow on button control device, seat will be lifted, when he presses that again, the lifting motion stops. Similarly, as user presses down arrow, seat will be lowered, when he presses that again, the lowering motion stops.

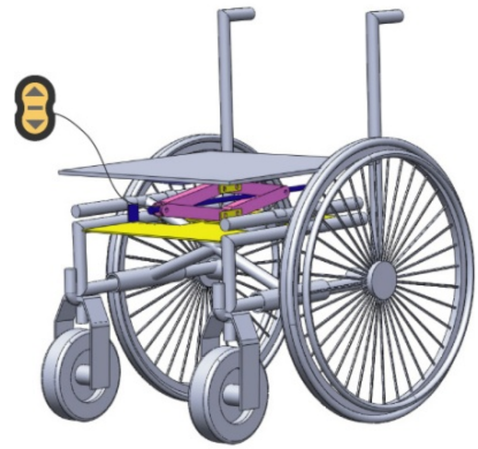


Figure 33: Electrical scissor jack concept

Benefit of this design is that depressing a button permits height adjustment, so the operation of this design is very flexible and accessible. It is supposed to provide a very smooth and stable movement of the height adjustment.

The primary limitation is weight. Since the power scissor jack can lift up to two tons, this is actually an over-engineered design. Secondly, a lot of noise is generated by the motor when adjusting the height. There is also a requirement of a battery which also increases weight and requires battery maintenance.

4.1.4.4 Concept E6: Pneumatic Bladder Lifting

Concept E6 is based on using of pneumatic bladder/bellow as a lifting device. The user operates a pump to inflate the bladder when increasing seat height and operates a valve to deflate the bladder when lowering seat height (Figure **34**). As described previously, bladder size can be adjusted to alter the lifting force and bladder volume.

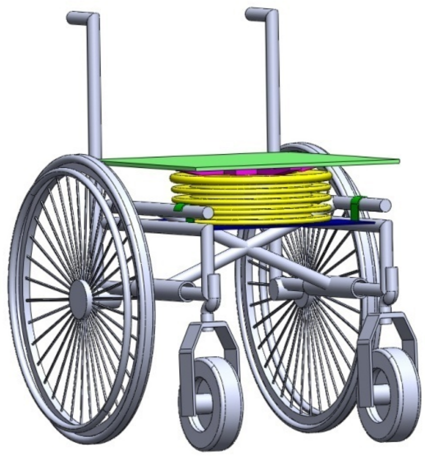


Figure 34: Pneumatic bladder lifting

One benefit of this concept is that air bladders are light and a person can be lifted up smoothly. The bladder can be pumped up either electrically or manually. A manual system requires operation of both a valve and pump and it may require a fair amount of effort to operate the pump. In addition, finding good pump locations may be difficult.

4.1.4.5 Concept G4: Linear Actuator

The linear Actuator concept is also a powered concept and operates off a 12-24 V battery system. Due to its length the actuator must be attached to the rear part of the frame and the front part of the seat which is propelled upward (Figure **35**).

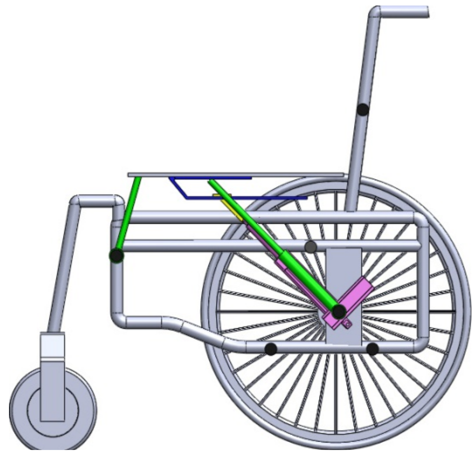


Figure 35: Highest seat position linear actuator concept

Linear actuators can provide a very stable and smooth linear movement. Battery power will permit use of a simple control device, so the user will experience a very simple and intuitive user experience.

Weight and battery maintenance are the biggest issues with powered device design. Linear actuators are also very expensive. . A linear actuator with 4’’ stroke can cost up to $120, which does not fit into the design criteria.

4.2 Fabrication

Selected concepts were fabricated as fully functional prototypes. These prototypes were designed to embody most functions of the design and interface. Stakeholder input did not identify a clear preference toward the manual or electrical mechanism. Therefore, concepts selected for fabrication included two lifting systems that are capable of being operated either manually or electrically. Electrical and manual versions of a scissor jack and a manual version of a pneumatic bladder were fabricated and evaluated.

To start prototyping the concepts, a universal platform was designed to fit on folding and rigid wheelchair frames, as the base for all the retrofit height adjustable components. The platform was made of an “H” shape 3mm aluminum and plastic composite sheet (Dibond), as well as four 3’’ height drop hooks (Figure **36**). An Invacare K0002 cross frame wheelchair and a Zippie rigid frame chair were used as the testing chair.

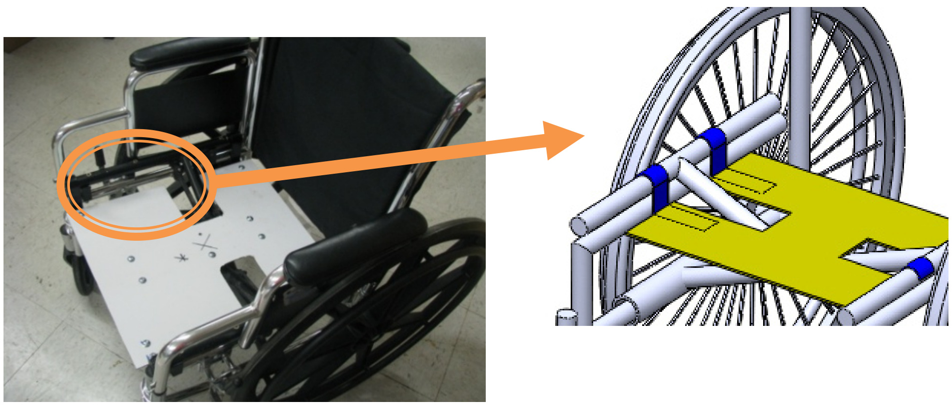


Figure 36: Platform on K0002 wheelchair

4.2.1 Prototype Implementation For User Test 1: Electrical Scissor Jack

4.2.1.1 Prototype Description

An electrical scissor jack prototype was implemented on the K0002 wheelchair. The scissor jack was mounted on “H” shape platform and operated using a 12V battery0 wired to a controller with “up” and “down” buttons (Figure **37**).

Figure 37: Overview of prototype with electrical scissor jack concept

4.2.1.2 Task Analysis

A Hierarchy Task Analysis (HTA) was used to analyze the actions required to raise or lower the wheelchair with the electrical scissor jack. Each action was labeled with a consecutive numbering. As some actions belonged to a larger category of "behavior", their numbers appeared to be "sub-numbering", such as 1.X, 2.4.X. A. (see Appendix B).

With each step, there is certain risk factor existing to potentially influence the safety status of user. The Risk Analysis is aiming at finding out these risks and providing possible solution to lower the risk factor. There are two situations in alleviating the risk.

First, it is certain component that causes certain safety hazard to user's use, so either replace this component or do further design on this component mechanism to increase safety level of whole device.

Second, if the risk existing in the application is unavoidable, the solution is to make further design on how to help user with acknowledging this risk and avoid doing the risky behavior intuitively.

4.2.1.3 Specification Evaluation

As shown in evaluation table (Table **14**), the electrical scissor jack prototype meets many of the targeted criteria but failed in reaching the required criteria of weight and cost, the prototype, as designed, also lacked the basic sitting stability.

4.2.1.4 Problem Screen and Possible Solution

a) The controller is easy to operate incorrectly because there is no indication on how to hold the controller to designate ‘up’ and ‘down’. Users can easily hold controller in either direction. Two solutions can be proposed here:

i. Instead of arrows, use printed letters “UP” and “DOWN”.

ii. Fix the handle in one position so use can only see or feel the controller in one direction.

b) The seat surface is wobbling because there is only a single point of support between scissor jack and seat pan.

c) Device is too heavy. Weight of the scissor jack is more that 9lbs, which is almost twice as much as the target design criteria.

d) The market price of an electrical scissor jack is \$60-\$120, about 20%-120% more than the target fabrication cost.

Table 14: Design criteria checklist of electrical scissor jack concept

	Design Specification	Yes	No	Detail
R	4" Height adjustment range	√		Electrical scissor jack has an adjustable height range of 9''
R	Uniaxial seat motion	√		
R	250lbs weight capacity			
T	Movement from extreme position requires <20 seconds	√		
T	Mechanical or powered operation			Powered
	If powered operation, 12V (or less) power requirements; easily accessible charging port; battery permits a minimum of 5 full transitions per day	√		
R	Designed as an add-on unit to existing wheelchairs	√		
T	Attachment is done using standard tools but drilling of frame is not allowed	√		
T	Operation while out of wheelchair	√		
T	5 lbs.: System weight		√	
T	Manufacture cost is less than $50		√	
R	Maintain stable during the height adjustment		√	

4.2.2 Prototype Implementation for User Test 2: Pneumatic Bladder Lifting

4.2.2.1 Prototype Description

The figure below shows a prototype for bladder concept implemented on Zippie wheelchair frame. It has a bladder with 5'' inflated thickness 13'' length (L) and 6'' width (W) (Figure **38**). A hand pump is used to manually inflating the two bladders. A pressure gauge was connected with bladder to monitor the pressure change inside the bladder (Figure **39**). To lift a 250 pound person, an inflation pressure of 2 psi was required.

Figure 38: Pneumatic bladder, 13’’*5’’*6’’each

Figure 39: Back view of implementation of bladder concept

A task analysis and risk analysis was performed to identify the steps required to operate this design and the safety risks of its operation. (Appendix A). . The greatest risk results from instability due to the flowing of air inside bladder. The use of two bladders covers a large area so the system is steady when fully inflated. However, when the bladders are partially inflated and there is a force imposed from the top, the bladders will compress differently to keep the inflation pressures balanced. User operation also requires design improvements. In current design, a butterfly valve is used to permit inflation or deflation of the bladders. Raising the seat requires the user to engage two separate devices, the pump and valve, which may cause problems for certain users.

In this design, the user must recognize seat position since only the lowest and highest positions will be stable and easily sensed. In the later design improvement, the seat height should be stable in all positions between the top and bottom.

4.2.2.2 Specification Evaluation

The bladder concept meets most of the required design criteria (Table **15**):

4.2.2.3 Problem Screen and Possible Solution

There are some functional problems existing within this design as listed,

a) Though seat panel is more stable at lowest position and highest position, it still wobbles when bladder is not fully inflated.

b) Due to volume of this bladder, using hand pump is rather energy and time costly. It takes a one-way pump 20 strokes to fully inflate two bladders.

Table 15: Design criteria checklist of bladder concept

	Design Specification	Yes	No	Detail
R	4” Height adjustment range	√		
R	Uniaxial seat motion	√		
R	250lbs weight capacity	√		
T	Movement from extreme position requires <20 seconds	√		
T	Mechanical or powered operation			Manual
	If powered operation, 12V (or less) power requirements; easily accessible charging port; battery permits a minimum of 5 full transitions per day	√		
R	Designed as an add-on unit to existing wheelchairs	√		
T	Attachment is done using standard tools but drilling of frame is not allowed	√		
T	Operation while out of wheelchair	√		
T	5 lbs.: System weight	√		
T	Manufacture cost is less than $50	√		
R	Maintain stable during the height adjustment		√	

To overcome those disadvantages, stabilizing systems were tried. Each concept used the bladder to provide lifting force, while the system’s stabilization was provided by the extra component.

Solution I: “Slider”

The first solution was adding linear drawer slide mechanisms to the back of seat to improve seat balance and stability. Two slides were connected a horizontal backrest member to insure that they moved in the same direction and with the same speed. The slides restrict side to side movement as the seat is moving along vertical direction (Figure **40**).

Figure 40: Implementation of slider stabilizer

However, several problems were still detected through a trial use:

a) Sliding part was very obtrusive at the back, which may interfere with the user's back.

b) Not every wheelchair has a horizontal back frame member to mount slider. This may cause retrofit problems.

c) Though this sliding component improves side by side balance of the seat, it does not really help with stability problem in fore-aft directions.

Solution II: "Linear Bearing"

To test the second stabilizer, the number of bladders was decreased to one to free up more space. Reducing the total bladder by 50% results in fewer pumping strokes required for user to operate. Of course, this doubled the required inflation pressure, but we determined that about 4 psi was still achievable for a manual pump. Secondly, assigning different functionality to different components simplifies analysis of the functional problems.

Figure 41: A linear bearing stabilizer

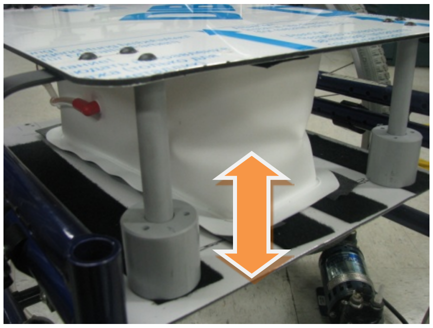


Figure 42: The work of linear bearing

A linear-motion bearing or linear slide is a bearing designed to provide free motion in one direction. In this solution, three linear bearings, all made of PVC, were fabricated and set up between seating panel and universal plate (Figure **41**). Each component was comprised of two parts, the bearing and the shaft. The bearing was the cylinder outer shell and shaft was the rod inside with flange at the bottom. To fix the object between two panels, a hole with the same diameter of the shaft was drilled on universal plate. The shaft went through this hole from bottom of universal plate with flange remains under the plate. The flange worked as a stopper when whole device is extended to the maximum length. Each bearing was placed on top of universal plate, concentric with the shaft to restrict its movement (Figure **42**). The longer the bearing is, the more straight motion it engages, but on the other side, more friction was produced along the motion.   The other end of shaft was fixed with seating panel. So as the bladder was inflated, it provided the force to raise the seat, and the shafts went along the bearings and confined the motion in one direction.

Problems identified with this prototype included:

1) During testing, the linear bearing produced too much friction when the seat was lifting.

2) The balance problem in front to end direction, since the three linear bearings are set up separately, each of their motion track is different from others.

Solution III: "Scissor Stabilizer"

A scissor stabilizer component, inspired by "scissor lift", was inserted between seat panel and universal base plate. The mechanism consists of linked supports in a crossed 'X' pattern called a “pantograph”. The fabricated prototype demonstrated that the scissor stabilizer combined the advantages from both the drawer slide and linear bearing. It did not require space outside of the two plates and the system maintained a consistent vertical motion. Another benefit of this stabilizer design is the storage advantage. Since bladder can deflate and scissor stabilizer collapses, the system will require a small shipping or storage volume.

The scissor stabilizer design was compatible with the universal plate on both K0002 folding wheelchair and Zippie rigid chairs.

4.3 Final Prototype

Final prototype used for evaluation resulted from iterative design of the pneumatic bladder concept. . A scissor mechanism, which was considered to be lifting components in other concepts, now played the role of “stabilizer”, and the bladder was used as for elevation. A set of “double scissors” were adopted to secure the stability and balance in every direction (Figure **43**).

4.3.1 Configuration

The final prototype of the seat height adjustment system was comprised of six components. A bottom plate mounts to the wheelchair frame using drop hooks and is the base for all the parts. A top plate also incorporated drop hooks help to stabilize it onto the frame while in the lowest position. The bladder, which is used as the lifting force, can be inflated and deflated to achieve the height adjustment. In this prototype, the bladder has a thickness of 6’’ when fully inflated, allowing for 4’’ height adjustability. The bladder volume is 6370.32 cc. When a 250lbs weight person is sitting on the bladder, air pressure inside the bladder is approximately 4 psi. The fourth component is the set of scissor stabilizers. They are positioned around the bladder in pairs and are connected to the top and bottom plates to move together (Figure **44**).

Figure 43**:** Final prototype

Figure 44: Inter-connected scissor system

The fifth component is the hand-held pump used to inflate bladder. In this prototype, a two way pump is selected to improve the efficiency, since it pumps airs when pushing and pulling the pump handle. The pump is 16inches long and has a volume of 378 cc. It takes 17 pumps to inflate the bladder to maximum height. The sixth component is the butterfly valve, which allows air to bleed out of the bladder to lower the seat. Bladder, valve and pump are all connected by ¼’’ diameter tubes. The valve and pump compose the operation interface. In this prototype, valve is securely attached to armrest while pump is placed in a cup holder.

Arrangement of interface components is an important factor influencing usability. The initial arrangement represented a starting point to obtain user feedback and offer high level of flexibility in changing the arrangement to improve usability and user satisfaction. Final arrangement will be determined after longer user trials that were not performed at this time (Figure **45**).

Figure 45: Pump and valve interface

4.3.2 Estimation of Cost

Cost and price are all important factors to measure the quality of design, since they predict the market performance of products. An estimation of cost was completed after the prototype was completed.

Table 16: Material list

Part	Size (inch)	Material	Order source	Quantity	Unit price
seat surface	15*19*1/4	aluminum painted sign sheet	Dibond	1	$71.64 for 4'*8'
support plate	15*19*1/4			1	
drop hooks I		Steel	Alibaba	4	$0.1-$ 0.9/each
drop hooks II		Steel		4	
"L" shape bar I	1*1*15 ½	aluminum	McMaster Carr 88805K47	4	$11.32 for 8'
"L" shape bar II	1*1*15	Aluminum		4	
Bar	3/4*1/8*12	Aluminum	McMaster Carr 89755K25	8	$7.73 for 8'
rod I	1/2(D)*17	Aluminum	McMaster Carr 86985K35	4	$31.29 for 6'
rod II	1/2(D)*8 3/4	Aluminum		4	
Bladder	13*6*5	polyurethane	Bena Inc.	1	$25.00/each
Pump		Plastic	ROHO® Hand Inflation Pump Dual Action(HP20)	1	$12.00/each
butterfly valve			Alimed 98SPH2-24	1	$17.00/each

Cost estimation for this height adjustment seat prototype consisted of a listing of components and assigning the purchase price of each (Table **16**). This table does not provide the estimated cost of manufacturing since it does not consider volume or other sourcing options. A refined cost estimate is provided for the final design discussed in the next chapter.

4.4 Testing and Evaluation

Testing began with two participants recruited from Center for Assistive Technology and Environmental Access (CATEA). The participants were not wheelchair users and testing was done to practice the protocol and make any adjustments to the design before testing wheelchair users. Wheelchair users were then recruited to evaluate the designed prototype. Wheelchair users had to be persons over 18 years old who are able to transfer independently from a seated posture. Exclusion criteria include persons who were unable to provide consent or were unable to consent in English. Persons requiring assistance to transfer from a seated position were also being excluded from the study. The methods were approved by the Georgia Tech Institutional Review Board and all subjects provided written informed consent before the evaluation.

A usability test of 8 wheelchair users was conducted at Center for Assistive Technology and Environmental Access (CATEA) and A.G. Rhodes Health & Rehab, both located in Atlanta, Georgia. The participants include 3 females and 5 males. All of participants use wheelchair as their primary tool for daily mobility activity, 5 also used walker as an assistive tool for moving inside and outside. Majority of those participants are over 50 years old. Among wheelchair users, half of them are able to use foot to propel the wheelchair. This group of wheelchair users had different kinds of disability such as arthritis, stroke, etc. (Table **17**).

Table 17: Participants profile

Participants Profile					
	Gender				
	F	M			
Number	3	5			
%	37.50%	62.50%			
	Age range				
	18-35	36-50	51-70	70+	
Number	1		2	5	
%	12.50%	0.00%	25.00%	62.50%	
	Device use to move around inside and outside				
	Cane	Crutches	Walker	Wheelchair	do not use
Number	2		5	8	0
%	25.00%	0.00%	62.50%	100.00%	0.00%

Testing consisted of three phases:

a) Engage seat height adjustment mechanism. This activity involved raising and lowering the seat with the manual pump.

b) Perform simple activities while seated in a test wheelchair. Activities were performed under two conditions: with available seat height adjustability and with no adjustability. This evaluation permitted observation of if and when seat height adjustment was engaged during activity.

c) Subjective feedback. Participants were asked to provide information about themselves and about their experiences with and opinions of the new seat design.

4.4.1 Activity 1: Engage Seat Height Adjustment Mechanism

At this stage, researcher provided detailed instruction on the operation of the seat height adjustment followed by a demonstration of how to use height adjustment during reaching and transferring. After this, participants were asked to transfer into the test wheelchair. The participant was asked to adjust the seat until familiar with its operation. Then he or she was asked to adjust the seat surface to three levels of height: low position (17.5’’ height), their typical position (approximately 19.5’’ height), and highest position (21.5’’ height). As participants performed the task, their behavior and actions were recorded

4.4.2 Activity 2: Perform Simple Activities While Seated In A Test Wheelchair

Activities were repeated with the adjustment feature engaged and disengaged. The order was randomized.

a) Researcher sets the test wheelchair’s seat height to typical wheelchair seat height of 19 ½ inches.

b) Participant was asked to transfer onto the wheelchair

c) For the disengaged function testing, participants performed requested activities. When height adjustment was engaged, participants were prompted to adjust the seat as needed to facilitate the activity.

d) Participants were asked to

1) Lift up the seat by as much as possible, measurement was done at the highest position achieved.

2) Move straightforward for 5-10 meters, go around a table and return to starting position. This involved propelling the wheelchair with one’s upper and/or lower extremities.

3) Pick up a small object (e.g. pill bottle) from the ground.

4) Retrieve a small object from a point above his or her head.

5) Transfer out of the wheelchair and onto a stationary chair

Task b, c, d, e were repeated with participants engaging the seat adjustment function, and disengaging the height adjustment function. Orders of tasks are randomized for each participant.

4.4.1 Activity 3: Information and Subjective Feedback

Participants were asked questions about their age, gender and mobility status followed by questions about the seat height adjustment feature. Likert Scale questions were asked in the survey to and users' choices were documented (Appendix B). Graphs were used to visualize users' satisfaction about experiencing the product use. Complaints about design were recorded from the subjective feedback section following the survey. Errors in operation were also tracked and recorded in notes as the participants were using the product.

4.5 Observations

4.5.1 Range Of Adjustment

Since pumping required certain amount of upper body strength, only 2 of the 8 participants were able to lift the seat more than 2'', and 3 were unable to complete a 1'' height adjustment. However 75% of participants considered the adjustment operation as easy or very easy. This contradiction was interpreted as meaning that operating the pump was easy but repeated pumping needed to raise the seat required too much effort resulting in a need to optimize pump selection and pump location (Figure **46**).

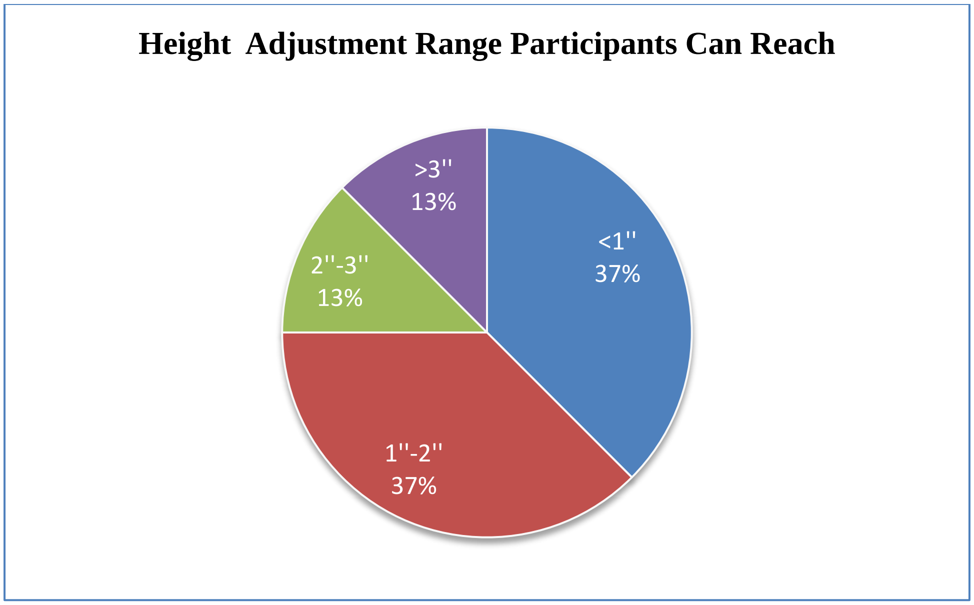


Figure 46: Percentage of participants able to reach specific heights

4.5.2 Survey Result

Half of the participants considered the seat height adjustment operation to be "easy", 1 out of 8 wheelchair users found it difficult to use. Half of the participants felt the height adjustment speed was adequate, while 2 users wanted a slower speed and 1 wanted a little bit faster speed. Only 1 out of 8 participants considered the motion speed to be too slow. In term of stability, all of the users found the seat to be always stable, proving the success of the balance and stability maintenance of the design prototype (Table **18**).

With respect to the value of the seat height adjustment feature, 3 of 8 users thought they would use the height adjustment function now and then but they didn't consider it to be a necessary component, 2 participants expressed the interest that they want to use it regularly, and 1 did not believe he would use it.. In response to the maximum acceptable weight of this retrofit unit, half of wheelchair participants felt the added function should no more than10lbs, and 2 of the testers said 15lbs was the maximum acceptable weight. The result of the question relating device cost revealed that 6 people would consider paying for the height adjustment feature, and 2 would consider it only if covered by insurance. Six of the 8 participants were willing to sacrifice the wheelchair's folding function by getting it height adjustable.

Table 18: Survey result of usability test

Survey Result of Usability Test					
1	How would you rate the seat height adjustment?				
	very easy	Easy	neither difficult or easy	Difficult	very difficult
response	3	4	0	1	
%	37.50%	**50.00%**	0.00%	12.50%	0.00%
2	How would you rate the speed of seat height adjustment?				
	too fast	acceptable but better to be a little bit slower	neither slow nor fast	acceptable but better to be a little bit faster	too slow
response		2	4	1	1
%	0.00%	25.00%	**50.00%**	12.50%	12.50%
3	Did you ever feel unstable while adjusting the seat height?				
	unstable when moving up and down	unstable only moving upward	unstable only when moving downward	unstable in highest seat position	always feel stable
response	0	0	0	0	8
%	0.00%	0.00%	0.00%	0.00%	**100.00%**
4	Do you think you would use the seat height adjustment if it were on your				

	wheelchair?				
	regularly use	might use it now and then but do not think it is necessary	might use it but do not know what I might use it for	never use	
response	2	3	2	1	
%	25.00%	**37.50%**	25.00%	12.50%	
5	What is the maximum allowable weight of the seat height adjustment device?				
	5lbs	10lbs	15lbs		
response	2	4	2		
%	25.00%	**50.00%**	25.00%		
6	How much would you pay for seat height adjustment?				
	<$50	<$100	<$200	only get if my insurance paid for it	not interested in having seat height adjustment
response	2	3	1	2	0
%	25.00%	**37.50%**	12.50%	25.00%	0.00%
7	The seat height adjustment will prevent your wheelchair from folding, does this change your opinion about the device?				
	still consider using device	no longer consider	not sure		
response	6	1	1		
%	**75.00%**	12.50%	12.50%		

4.5.3 Design Weakness and Complaints

During the testing process, all of users' comments, complaints, as well as recommendations were recorded and documented for further analysis. The top complaint about the prototype was the valve position, which hindered users from reaching the wheelchair's wheel lock. Some users found the valve contacted the leg while seated in the chair. The second most mentioned weakness in this design is the effort required to change seat height with the hand pump. For those who have arthritis or weakness due to stroke, it was impossible for them to use both hands to operate the pump (Figure **47**).

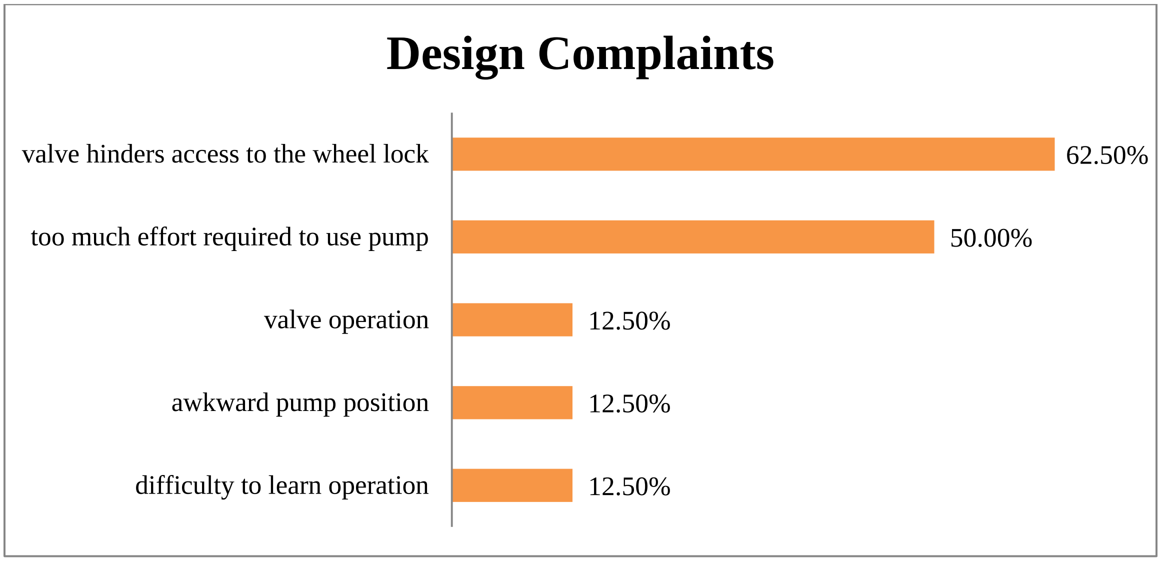


Figure 47: A chart of design complaints provided by wheelchair users

Some users questioned the consistency of lifting and lowering the seat, since lowering is so simple and fast while going up requires a lot of effort. . One user pointed out the fact that the inconsistencies affected learning this manual operation. Users suggested using a motor and battery to inflate the bladder to make it easier to use. The placement of pump also appears to be a problem. Since the pump was attached to the legrest, it prevented the legrest from swinging away and being removed. One user suggested putting the pump between the support plate and seating surface. This seems to be a commonly used place for wheelchair users to reach and grab accessories.

Some other design problems were also observed as the users were performing the task. Almost every participant forgot to close the valve as they began to lifting the seat during the first trial of the height adjustment. This mistake occurred less often after some practice. This problem can be solved by using a momentary pneumatic push valve, which automatically closes after being released. Another failure of height adjustment happened when one of the participants wanted to lower the seat while he was out of the wheelchair. The pneumatic design requires weight on the seat to deflate the bladder.

4.5.4 Other Observations

While users were experiencing the current design, some interesting things were noticed. Despite no indication that the height adjustment speed could be controlled, some users intuitively figured out that by slowly rotating the butterfly switch, they can successfully find a way to sense and control the adjustment speed by listening to the sound of air outlet.

With respect to cost, the total cost of the design prototype is 50% more than participant's expectation, which would not be acceptable. A revised cost estimate will be done for the final design by considering sourcing of materials such as pump, valve and drop hooks.

Chapter 5

FINAL DESIGN AND DISCUSSION

5.1 Criteria Revision

According to participants' experience with the functional prototype, adjustments were made to the design criteria and device design. Testing indicated that wheelchair users have different ideas and feedback regarding the design of height adjustable seat wheelchair. It proves that user's attitude toward product design can change a lot by actually using it. Factors such as cost and weight can be highly variable, based on users' satisfaction upon product user experience.

As a result from the usability test, the acceptable maximum add-on weight of the height adjustable unit was set to be 10lbs. The maximum cost of the add-on system parts was set at around $100.

New criteria were also defined based upon users' feedback. First of all, wheelchair users did not like the position of the valve and pump, since their operation interfered with operation of the wheel lock and footrest. Participants responded that they wanted a valve that can automatically close after being opened. So in the new criteria, several universal design principles, such as "size and space to approach" "tolerance for error" have to be applied.

Several adjustments on design criteria have been made according to usability results. A new list of design criteria include:

a) The seat-to-floor height adjustment is ranging from 17 ½'' to 21 ½'', with the neutral position of 19½''high.

b) The seat height adjustment is vertically up and down, seat surface remains horizontal during the adjustment.

c) The seat height adjustment unit can be retrofitted into a manual wheelchair seat frame with the width of 18’’ and depth of 16’’, the wheelchair requires having armrests available.

d) The seat height adjustment should support a user that weighs up to 250lbs.

e) Wheelchair user can maintain stability at any height during height adjustment.

f) The seat height adjustment unit should weigh no more than 7lbs.

g) It takes no more than 20 seconds for user to reach either maximum high or the maximum low setting.

h) Manufacture cost of the retrofit unit should be less than $100.

i) The seat height adjustment should be achieved by manual operation and no battery is required.

j) Set up of unit should place no obstacle to the performance of armrest and legrest. Operation part of unit should be easy to approach.

5.2 Design Revision

Figure **48** shows the revised version of height adjustable wheelchair seat design. Three major modifications were made to the design after user testing:

1) Redesign the pump
2) Redesign the valve
3) Add the protection shell between seat and support surface

In addition, the design was revised to optimize the amount of materials and components required. Finally, using the new list of components, manufacture cost estimation was performed in order to estimate the cost to the customer.

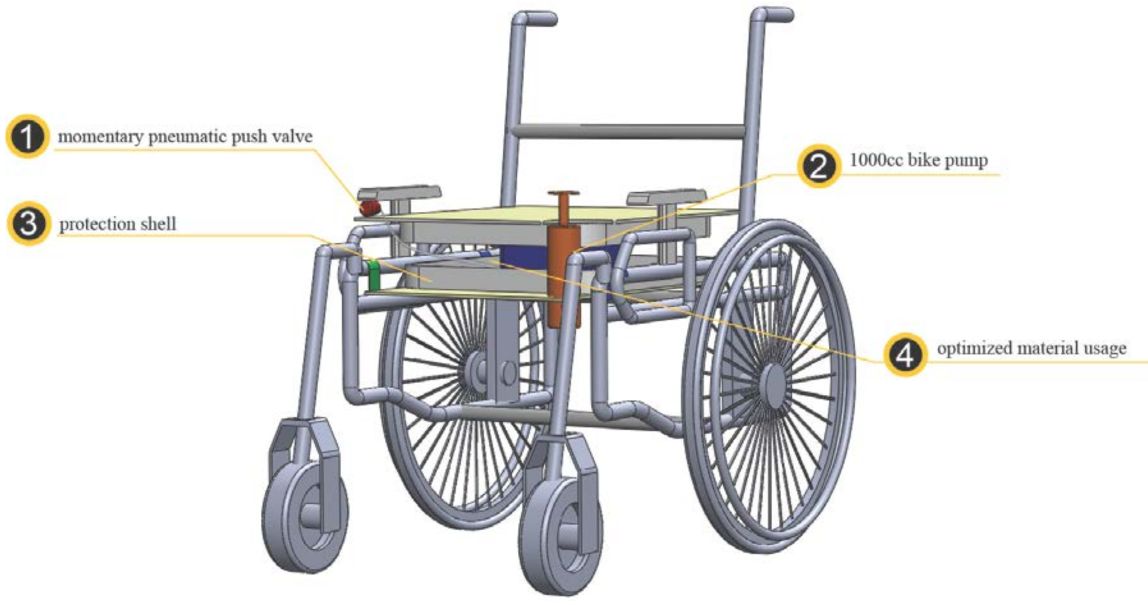


Figure 48 Revised height adjustable wheelchair seat design

5.2.1 Pump design

Pump will be located on the side and mounted between the seat plate and bottom plate. The seat plate will have a cut out along one side to provide clearance for the pump handle. A two way pump with 1000cc volume is going to be fixed at the edge of supporting plate with its handle protruding out of cut-out. When not in use, the top of the handle is flush with seat surface, and during use, the user pulls the handle out of cut-out (Figure **49**).

Figure 49 Revised pump design

Regarding space allocation of revised pump design, Figure **50** shows the possible location of the pump. As width of seat panel is extended to cover the side frame, a quarter circle shape intent can be cut at seat surface. The handle of the pump protrudes through this intent. Cushion with a 15’’-17’’ width can still be able to fit on top of seat surface.

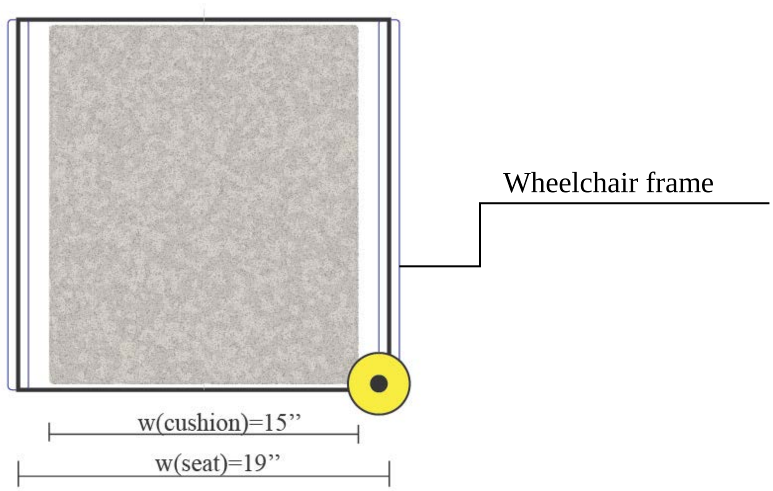


Figure 50 Dimension for placement of bike pump

5.2.2 Valve design

Consistent with the principle of “tolerance for error’’, a momentary pneumatic push valve, also named “push button” valve will be used instead of the butterfly valve. Instead of rotating a lever, users actuate the valve by pressing a button. This will significantly improve convenience and safety of the user interface. Since the force required to press the button is dictated by air pressure inside the bladder, the force must be assessed and positioned so users can operate it. The bladder should require less than 4psi to lift a 250lbs person, so push activation is expected to be low, but must be evaluated further.

Placement of the valve was changed according to users’ feedback. In the revised design, the valve will be placed under armrest (Figure **51**). At this position, the user has easy access to valve button without needing to look for it, and push button valve can be made in very small size so that it will not affect any visibility and access to the wheel lock. This location of pump button has one drawback that it will prevent armrest to be removed from chair. However, according to observation, target users who are elderly are in need of armrests to perform different activities such as sit-to-stand and reach things. For this group of users, armrests are not often removed, however, for other users, alternative locations for the push button valve must be investigated. .

Figure 51 Valve attached under armrest

5.2.3 Protection Shell

Two “fences” were installed onto both top surface and support plate to cover the lifting mechanism. Since the scissors have many pinch points, the setup of fences will protect users from touching the mechanism with their fingers. Scissor lifting structure is hidden inside the “fences”. The fences are touched to each other when seat is at lowest position, while a gap will show up as the seat surface is going up (Figure **52**).

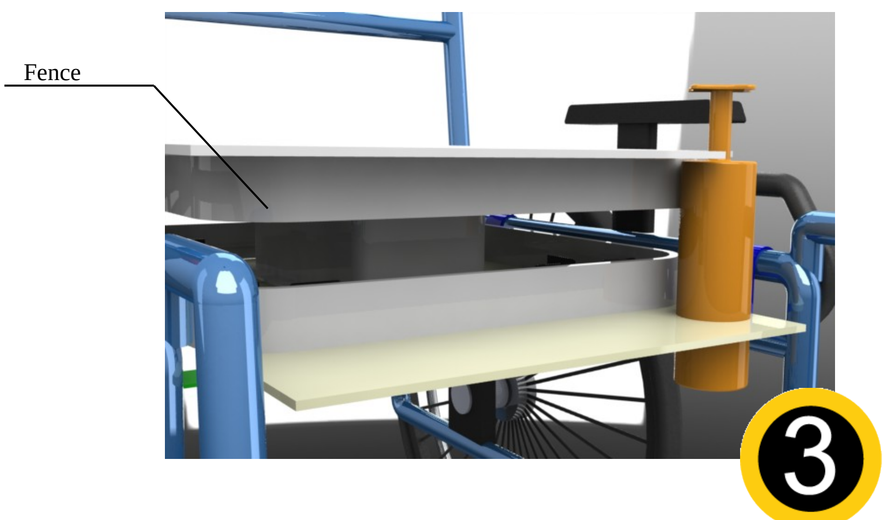


Figure 52 Protection shell

5.2.4 Material Usage and Optimization

Overuse of materials added unnecessary weight to the lifting system prototype. Two design changes were made to optimize material usage. First, the 4 drop hooks on the seat plate were removed. By simply extending the width of seat, it can achieve a similar function by resting on the wheelchair frame as the seat lowers.

The second refinement concerned the “L” shape aluminum bars used to mount the stabilizers. Repeated use of a single fixture will replace the long “L” shape aluminum bar. Each fixture has a size of 2 ¼’’ by 2 ¼’’ in area and 1 ¼’’ by height, with two slots and two holes on the ridge (Figure **53**).

By rotating the fixture quarterly, it is easy to match two of them and connect them with solid rod (Figure **54**). The revised fixture will be molded from lighter material such as plastic. Hole on the fixture serves as a fix point and the slot is for the other side of scissor piece to move back and forward as the whole structure is expanding and collapsing.

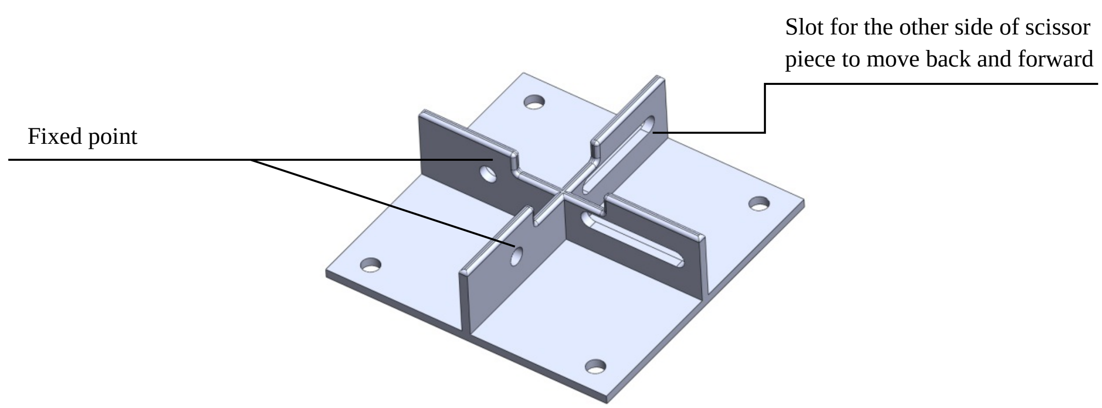


Figure 53 Fixture design

The improved design on fixture will not only optimize material use, it will also make assembling process easier and faster, as well as reduce the package size and weight. The final assembling of stabilizing frame is secured by 8 fixtures, all identical pieces that can be mass produced.

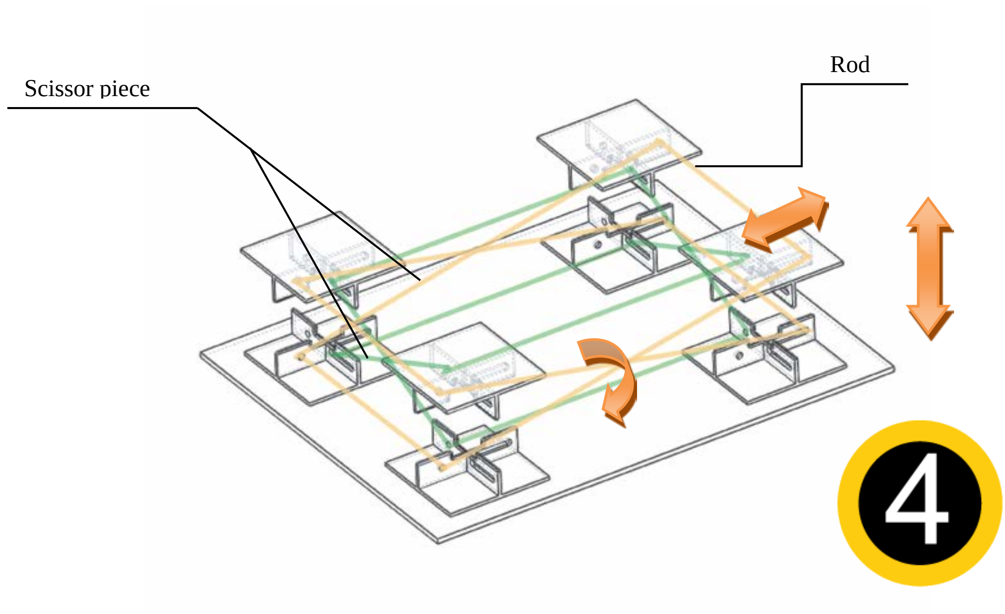


Figure 54 Connect the fixtures and set up the frame

5.2.5 Cost Estimation Optimization

A cost estimate of the revised design consisted of identifying sources of components and materials. Alibaba (alibaba.com, 1999-2011), an e-commerce site, was used to search for components. . Costs were estimated using a volume of 200 pieces. . Single product cost is a result of the gross price divided by 200, plus a 30% margin which may include shipping, insurance etc.

The resulting cost estimates indicated that the revised design and improved sourcing lowered the cost of each system by $73.34 or 49% compared to the original prototype. The revised product cost is within the acceptable price range of participants (Table **19**).

Table 19 Revised cost estimation

Material Cost for 200 units					Single price	
Material	order source	quantity	unit price	price	Prototype cost	add margin
aluminum painted sheet	Dibond	25.00	71.64	1772.34		
fixture		1600.00	0.2	320		
aluminum rod	McMaster Carr 86985K35	72.00	31.29	2252.88		
bladder	Bena Inc.	200.00	20	4000.00		
Pump	Alibaba	200.00	3.5	700.00		
momentary pneumatic push valve	Alpine Echo	200.00	12	2400.00		
drop hooks I	Alibaba	800.00	0.5	400.00		
				11863.88	59.32	$77.12

5.3 Conclusion

The design of Height Adjustable Wheelchair Seat followed a User Centered Design (UCD) method. The result of final design resulted from assessing user needs, reviewing mechanisms and applications, fabricating prototypes, and estimating costs. This iterative process resulted in a final design meets stakeholders' needs and requirements. However, further modification and iteration are still required to optimize performance of the product.

Implementation of this project illustrates that design is a result of resolving conflicts and making compromises. The choice of bladder inflation and the placement of pneumatic button are all imperfect options, but the design combination best fits users and market requirements.

It also proves that a preparation for design optimization is necessary in UCD approach. In the final design, although the cost of proposed fixture is unknown before it is actually manufactured, it is promising to have the concept established based on previous evaluation and analysis so that more effort can be made to achieve its goal.

As it concludes, design of the height adjustment seat can be a never ending process based on different users basic requirements. Every design and prototype can play the dual-role of an outcome from previous version, as well as a reference to inform the next version. Power of the design concept is summarizing previous study to envision the future work and find out the solutions for better usability.

APPENDIX A:

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology

Project Title: a User Testing of Height Adjustable Wheelchair Seat Design

Investigators: Dr. Stephen Sprigle, Yiran Li, Deborah Michael

Physical Therapist: Stephen Sprigle, Deborah Michael

<u>Research Consent Form</u>

You are being asked to be a volunteer in a research study being conducted at Georgia Institute of Technology (Georgia Tech). This study looks at the usability of a height adjustable wheelchair seat design.

<u>Purpose:</u>

The purpose of this study is to evaluate the usability of the new design and analyze the user feedback to make necessary modifications and improvements on the design concepts.

<u>Exclusion/Inclusion Criteria:</u>

Only persons who are at least 18 years of age and are able to give consent are eligible to participate. The participants should be able to get out of a chair by themselves in a safe manner.

<u>Procedures:</u>

If you decide to be in this study, you will be asked to do the following things:

1. You will be asked to sit on a wheelchair the newly designed height adjustable seat.
2. You will be taught how to adjust the seat height, and then be asked to adjust the seat surface to three different heights. Adjustment will be done by operating a crank or handle or depressing a switch.
3. You will be asked to move around the room while seating in the wheelchair two times. During one trial, we will set the seat height of the wheelchair. During the other trial, you may adjust the seat to which ever height feels most comfortable.
4. You will be asked to pick up a small object from the ground while seated in the wheelchair. This will be done two times at different seat heights.
5. You will be asked to reach an object positioned above your head. This will be done two times at different seat heights.
6. You will be asked to transfer from the wheelchair into another chair. This will be done two times at different seat heights.
7. You will also be asked to complete a short survey.

The total time of the test sessions should be no longer than 1 hour.

Risks or Discomforts:

There are no special risks or discomforts associated with participation in this study. As with normal participation in any daily activity, there is always a small risk for injury.

To minimize risks, we will always explain the requested activity and ask if you are comfortable in performing the activity. You will be allowed to rest as much as you need between any of the stated activities. As you are performing any of the stated tasks, you will be supervised by a licensed physical therapist. If you seem to be unsteady while performing an activity, you will not be asked to continue that task.

Benefits:

There may not be any direct benefits associated with your participation in this study. We do expect that your participation will help us better understand the usability of height adjustable seat design on wheelchair. It will also help us to better explore and develop assistive technology on wheelchair design. With increased knowledge, we may be able to come up with more ideas to facilitate wheelchair users with daily activity and reduce the difficulties and risk of doing some tasks.

Compensation to You:

If you participate, you will receive a small $25 stipend or Gift Card in appreciation for your time. If you are employed by Georgia Tech mobilityRERC, you will not qualify for the stipend.

Confidentiality:

The following procedures will be followed to keep your personal information confidential in this study: The data collected about you will be kept private to the extent allowed by law. To protect your privacy, your records will be kept under a code number rather than by name. Your records will be kept in locked files and only study staff will be allowed to look at them. Your name and any other fact that might point to you will not appear when results of this study are presented or published. Your privacy will be protected to the extent allowed by law. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB may review study records. The Office of Human Research Protections and/or the Food and Drug Administration may also look over study records during required reviews.

Costs to You:

There are no costs to you, other than your time, for being in this study.

In Case of Injury/Harm:

If you are injured as a result of being in this study, please contact Dr. Stephen Sprigle at the Georgia Institute of Technology at telephone (404)894-4960. Neither the Principal Investigator nor the Georgia Institute of Technology has made provision for payment of costs associated with any injury resulting from participation in this study.

Participant Rights:

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.

- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study:

- If you have any questions about the study, you may contact Dr. Stephen Sprigle at (404)894-4960.

Questions about Your Rights as a Research Participant:

If you have any questions about your rights as a research participant, you may contact Ms. Melanie Clark, Georgia Institute of Technology, Office of Research Compliance at (404) 894-6942.

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

____ __________

Participant Name (printed) Signature Date

____ ____________

Signature of Person Obtaining Consent Date

APPENDIX B:

PARTICIPANT USER TESTING SURVEY FOR HEIGHT ADJUSTBLE SEAT WHEELCHAIR DESIGN

Dear participants,

Thank you for participating in the user testing of our height adjustable seat wheelchair design. We appreciated all the effort you have made in improving our design by answering the following questions. Any of your comments and feedback concerning our product are highly recommended.

User Profile

Please circle the option which best fits your situation.

Gender: Female Male

Age: 18-35 36-50 51-70 70+

What devices do you use to move around inside and outside (check all that apply)

- Cane
- Crutches
- Walker
- Wheelchair
- I do not use any mobility aids

Survey (only wheelchair users will answer the final 5 questions)

Please select the option which best fits your rating with the testing wheelchair.

1. How would you rate the seat height adjustment?
   a. very easy
   b. easy
   c. neither difficult or easy
   d. difficult
   e. very difficult

2. How would you rate the speed of seat height adjustment
   a) The adjustment speed was too fast
   b) The adjustment speed was acceptable but I'd like it a little slower
   c) The adjustment speed was acceptable but I'd like it a little faster
   d) The adjustment speed was too slow

3. Did you ever feel unstable while adjusting the seat height?
   a. I felt unstable when it was moving up and down
   b. I felt unstable only when moving upward
   c. I felt unstable only when moving downward
   d. I felt unstable only when in the highest seat position
   e. I always felt stable

4. Do you think you would use the seat height adjustment if it were on your wheelchair?
   a. I would use it regularly
   b. I might use it now and then but I do not think it is necessary
   c. I might use it but do not know what I might use it for
   d. I would probably never use it

e) What is the maximum allowable weight of the seat height adjustment device?
   1) 5 pounds
   2) 10 pound
   3) 15 pounds

f) How much would you pay for seat height adjustment?
   1) No more than $50
   2) No more than $100
   3) No more than $200
   4) I would only get it if my insurance paid for it
   5) I am not interested in having seat height adjustment

g) The seat height adjustment will prevent your wheelchair from folding. Does this change your opinion about the device?
   1) I would still consider using the device
   2) I would no longer consider using the device

h) Do you have any other comments and opinions about this new wheelchair function?

APPENDIX C:
TASK ANALYSIS

"Concept: Manual Bladder"
The bladder design consists of bladders that inflate and deflate to raise and lower the seat. In this task analysis, lowering the seat involves bleeding air through a manual valve and raising the seat involves use of a manual pump. Electromechanical operation is possible but is not covered here

Task Analysis (HTA)						Risk Analysis
1.	Lower the seat	1.1	Reach valve			Where is the valve located? How easy to reach the valve?
		1.2	Lock wheelchair			It is highly possible that user will forget this step. Necessary design is needed to guarantee user's safety even wheelchair is not locked.
		1.3	Lower the seat	1.2.1	Rotate the valve handle to open the valve	How to indicate direction of valve operation?
				1.2.2	Keep balance as the bladder deflates, until 1. bladder is totally deflated and seat cannot go down anymore 2. user is satisfied with current seat height	How fast is the "down" activity? How stable user will be during the motion? Can the user acknowledge bladder is deflated clearly? Does a pinch point exist when lowering the seat?
				1.2.3	Rotate the valve handle to close the valve	How to indicate direction of valve operation?
		1.4	Move hand away from valve and switch to other activity			Has the system stopped completely right now? Is place of controller potentially hinder user's next activity?
2.	Raise the seat	2.1	Reach and grab pump handle			Where is the pump handle located? How easy to reach the pump handle?
		2.2	Lock wheelchair			
		2.3	Rotate the valve handle to close the valve			
		2.4	Taking advantage of upper body weight, pressing pump by hand	2.2.1	Put hand over pump handle	
				2.2.2	Press pump by using upper body strength	Is there any risk that user will lose balance and fall of chair doing this action?
				2.2.3	Release pump by using upper body strength	
		2.5	Repeat 2.2.2-2.2.3 for couple of times, until a. user is satisfied with his current position (lower than highest position) b. bottom is very stable, indicating it is the max thickness of bladder.			What if user cannot recognize that the bladder is full already? Is there any risk that the bladder is going to explode because of overloaded air?
		2.6	Stop pumping			
		2.7	Rotate the valve handle to close the valve			
		2.8	Lock wheelchair			
		2.9	Move hand from pump handle and switch to other activity			

“Concept: Electrical Scissor Jack”

Electrical Scissor Jack concept is comprised of a car jack set and the universal plate to support the jack. A button controller is connected with the car jack body, and a 12V battery is required to power up the jack movement.

Task Analysis (HTA)				Risk Analysis
1.	Lower the seat	1.1	Reach controller	How easy to get the controller? Is the controller going to be fixed at one position or random positioned? Is the controller either too big or too small to hold in hand?
		1.2	Press “down” button	Is the button logo clearly marked? What kind of feedback will the user get by doing this action?
		1.3	Keep pressing “down” button until the seat is not able to lower down anymore	How fast is the “down” activity? How stable user will be during the motion? What happened if the battery dies during the movement? Can the user acknowledge stop motion clearly?
		1.4	Release “down” button	How long is system’s response time as user release the button? Will there be any inertia accompanies?
		1.5	Replace controller and switch to other activity	Has the system stopped completely right now? Is place of controller potentially hinder user’s coming activity? What happened if battery dies at lowest position?
2.	Lift the seat	2.1	Reach controller	How easy to get the controller? Is the controller going to be fixed at one position or random positioned? Is the controller either too big or too small to hold in hand?
		2.2	Press “up” button	Is the button logo clearly marked? What kind of feedback will the user get by doing this action?
		2.3	Keep pressing “up” button until a. User is satisfied with his current position (lower than highest position) b. Seat is not able to move up anymore	Any indicator, either tactile, audio or visual symbols to give a hint along with the movement and preferred location?
		2.4	Release “up“ button	Is the button logo clearly marked? What kind of feedback will the user get by doing this action?
		2.5	Replace controller and switch to other activity	Has the system stopped completely right now? Is place of controller potentially hinder user’s coming activity? What happened if battery dies at lowest position?

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